

Petrological and Statistical Studies of the Limbiko Bauxite Deposit, Republic of Guinea

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Abstract

The increasing demand for Aluminium pushes the miners to multiply the research in order to answer this demand. The objective of this work is to characterize the bauxitic deposit of Limbiko. The methodology consists in collecting samples, and establishing stratigraphic logs, sections and geological maps. The analyses were carried out in the laboratory of the Company des Bauxites de Guinea. Statistical methods were used to process the geochemical data. The study area is characterized by sedimentary formations of the Devonian, in which the dolerites of the Mesozoic were injected. It is on these Devonian and Mesozoic formations that the Limbiko bauxite deposit was developed. The stratigraphic logs show the succession of formations. The parent rock is surmounted by an alteration crust. The petrographic study is based on the bauxitic and transitional zones characterized by ferruginous laterites. Both zones contain some ferriplantite. Mineralogical analysis shows the presence of gibbsite, goethite, alumogoethite, rutile and clay minerals. The geochemical study of the major elements shows that the more the contents of SiO₂, Fe₂O₃ decrease, the more the content of Al₂O₃ increases and those of TiO₂, Al₂O₃ increase in the same direction. The PCA confirms the mineralogical results by classifying the samples into clay, bauxite and ferrite.

Keywords

Bauxite, Alteration Crust, Aleuro-Argillite, Dolerite, Gibbsite

1. Introduction

Bauxite is the main aluminum ore consisting essentially of one or more alumina

hydrates and impurities. The main minerals are $Al(OH)_3$ gibbsite, boehmite and sometimes AlOOH diaspora, but they are almost always accompanied by iron, Fe_2O_3 hematite or FeO(OH) goethite, titanium, rutile and TiO₂ anatase oxides and clay minerals, mainly Kaolinite $Al_4 \cdot Si_4 \cdot O_{10}(OH)_8$ [1]. Gibbsite-rich bauxite is preferred because it can be refined at lower mineralization temperatures than other types of alumina-containing minerals [2]. It is generally reddish-brown in color, but it can also be white, copper-colored, or yellow, depending on the type and concentration of iron minerals present. It can have a wide variety of different textures, and usually has a dull to the earthy chandelier, and may look like clay or earth [3].

Bauxite is formed as a residual product, resulting from the chemical weathering of aluminum silicate-containing rocks, over millions of years [3] [4]. It generally appears in the form of a thin layer (usually 2 to 5 m thick) on the surface or in the vicinity thereof.

Several criteria were used to classify bauxite deposits, including type, mineralogy, chemical composition, geomorphology and type of parent rock. Bogatyrev & Zhukov [5] classified bauxite deposits into three genetic groups: lateritic bauxite, sedimentary bauxite and karstic bauxite. In general, strong *in situ* lateralization of aluminosilicate rocks generates lateritic bauxites [5]. Sedimentary bauxites are primarily the product of the accumulation of lateritic bauxite deposits transformed by sedimentation processes [5] [6]. Karstic bauxites are limited to karstic carbonate rock formations [7].

Bauxite deposits are widespread, mainly in tropical areas, where there is intense weathering [8]. West Africa and Brazil have the largest bauxite reserves in the world [9]. In West Africa, bauxitic deposits are located on either side of the West African shield uplift axis [9].

In 2019, global bauxite production is around 348 million tons, with annual growth of more than 5% over the last decade, largely due to increased Chinese demand. The main producing countries are Australia, Guinea, China, Brazil and India [10].

The discovery of bauxite in Guinea dates back to 1819 by G. Mollien when analysis of rock samples at the Royal School of Mines in Paris revealed the existence of minerals rich in alumina. It took another century (precisely in 1920) for the Society Bauxites of Midi (a French subsidiary of Alcan) to become interested in the country's bauxitic deposits [11]. Several other studies have since been carried out leading to the discovery of important deposits.

Guinea has the world's largest bauxite reserves. With a high alumina content, Guinean bauxites are estimated to be over 40 billion tons, of which 23 billion tons are located in the Boke region [12].

The Boke region where the Limbiko deposit is located was raised to 1/200,000 by Samozvantsev *et al.* [13]. The study identified areas of high bauxitic potential, not the assessment of reserves.

To continue in the same dynamic, several studies have been undertaken in this region, notably on the Limbiko deposit [14] [15] [16] [17] [18]. Some of

these studies focus on the geological study, others on the assessment of resources or reserves. No petrographic, mineralogical, geochemical and statistical studies of the entire deposit have been carried out involving methods that can demonstrate the chemical and mineralogical composition. Today, with technological and scientific progress, it is possible to provide satisfactory answers to this problem. Therefore, the main objective of this work is to conduct a petrographic, mineralogical, geochemical and statistical analysis of the different types of bauxites in the Limbiko deposit and their parent rocks.

2. Geological Setting

2.1. Geology of the Study Area

Located in the north-west of Guinea between 10°30' and 11°45' latitude North, 13°45' and 15°00' longitude West, the Boké prefecture extends over 11453 km² and belongs to the natural zone of the Lower Guinea (**Figure 1**), the region of studies belongs to the coverage of the Guinean platform located in the south-west part of the West African craton [13] [16] [17].

This sedimentary cover is characterized firstly by Ordovician formations consisting of fine-grained quartz sandstones, sometimes feldspathic, with intercalations of aleurolites [19]. In the same logic, the Silurian formations consisting of finely bedded black mudstones, compact mudstones, aleurolites and micro oolithic iron lenses with intercalation of quartz sandstones lie in agreement with the Ordovician [19]. The Devonian, composed of quartz sandstones and alternating mudstones and aleurolites, is concordant with the Silurian [17].

During the late Paleozoic and Mesozoic, the study area experienced significant tectonic activity related to the break-up of the Gondwanaland continent and the opening of the Atlantic. This activation was marked by the formation of a NE-SW transform fault system and several secondary faults, through which trapean intrusions penetrated. These magmatic intrusions are represented by dolerites (basic rocks) [17].

The study area is characterized by Cenozoic deposition by marine formations (quartz sands, bedded clays) and weathering crusts of Paleogene age that lie uncomfortably on top of Paleozoic formations. Neogene conglomerates lie concordantly on the Paleogene. Quartenary deposits represented by sands, sandy silts, marine kaolinitic clays, fluvio-lacustrine clays and sands exist on the coastal plain and are sometimes located in river valleys [17] (Figure 1(c)).

2.2. Geology of the Limbiko Deposit

The Limbiko bauxite deposit is represented by Devonian aleurolites, aleuro-argillites and argillites, into which Mesozoic dolerite sills and dykes are injected [17].

In the study area and adjacent areas, the oldest faults are NE-SW trending, whereas the NE-trending brittle dislocations are related to recent transform faults (**Figure 2**). The last and most important tectonic activation occurred during the neotectonic stage when the inherited landforms were established [13].



Figure 1. Presentation of the study area; (a) Location of Guinea; (b) Location of the study area; (c) Geological map of the study area. 1—Non-differentiated deposits: sandy and sandy rubbing lime with gravel, galets deleuvio-proluvionnaires; 2—Non-differentiated deposits: clay sands and clay limon, sands, gravels, aluvionnairs; 3—Laterized rocks: sands, sandy limons, conglomerates; 4—Mesozoic Dolerites; 5—Devonian Faro Suite; 6—Silurian Telemile suite; 7—Ordovician Pita Suite; 8—Granites and granodiorites to biotitles; 9—Bankruptcy Fails; 10—Assorted Fails; 11—Streams; 12—Geological Limits Established; 13—Cities; 14—Deputy Prefecture; 15—Roads.

The Limbiko bauxite deposit underwent tectonomagmatic reactivation in the Mesozoic that favored the emplacement of dolerite sills. These sills have a sub-concordant and gently sloping disposition with respect to the surrounding Devonian sedimentary rocks. The thickness of the dolerite sills varies between 5 and 35 m. The dolerites are widespread in the deposit and represent up to 45% as the bedrock of the deposit, alternating with the Devonian sedimentary rocks whose thickness is equal to that of the sills. Our study area is related to the strongly dissected asymmetrical Bowes whose relief rises in a gentle slope and in step from north to south [15].



Figure 2. Geological map of the deposit ([15]; modified by this work). 1—Gelled bauxites derived from aleuro-argillites; 2—Apodoleritic gelled bauxites; 3—Lateritic bauxites derived from aleuro-argillites; 4—Apodoleritic lateritic bauxites; 5—Bauxite laterites derived from aleuro-argillites; 6—Apodoleritic laterite bauxites; 7—Sedimentary lateritic formations Miocene station covering the dolerites; 8—Sedimentary lateritic formations Miocene station covering the Devonian rocks; 9—Faults; 10—Watercourses; 11—Rural track; 12—Villages; 13—Irrigated zone; 14—Section along Line A and B.

3. Materials and Methods

3.1. Materials

The main material for this study is the bauxite deposit of the Limbiko plateau. The tools used to carry out this study are an Estwing geologist's hammer and an Atlas Copco drill for sample collection, Adobe Illustrator CS software for digitising maps and stratigraphic logs, a polarising microscope for petrographic analysis of the samples, an ADP-1 diffractometer to determine the mineralogical composition, an ICP-AES spectrometer to identify the major elements, Triplot v4.1.2 software for the creation of ternary diagrams and Statgraphic Centurion_18.1.12 software for the processing of geochemical data using statistical methods.

3.2. Methods

During our internship period from 22 January to 25 March 2020 at the Compagnie des Bauxites de Guinée, geological studies (core analysis, stratigraphic logs, cross-sections and geological maps), as well as several samples, were collected on the Limbiko bauxite plateau. The samples were sent to the Compagnie des Bauxites de Guinée laboratory in Kamsar for analytical studies. About fifty (50) samples were prepared for macroscopic and microscopic analysis. The study of lateritic rocks with a polarising microscope presents a certain difficulty. This is due to the very small (sub-microscopic) size of the phases and often to the presence of opaque areas in the highly ferruginous varieties. Therefore, the most interesting samples were studied at the Chair of Petrology and Mineralogy of the Lomonosov Federal University in Moscow using the electron microscope and the microprobe. Subsequently, thirty-six (36) samples were analysed by X-ray diffraction to determine the mineralogical composition. In the same way, thirty-six (36) samples were studied for the identification of major elements in the bauxite samples. The method consists of etching the sample on a hot plate in three (3) steps: 1) by the mixture (Hf + HCl) then 2) by the mixture (HNO₃ + HCl) and finally 3) by HCl. The bauxite samples were analysed at the Institute of Steel and Alloys, Moscow, Russia by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) for the detection of major elements. All the samples were projected into model ternary diagrams (Al₂O₃-SiO₂-Fe₂O₃) allowing them to be classified according to these three elements. Finally, statistical methods (Bravier-Pearson correlation, Principal Component Analysis 'PCA' and Clustering) were applied to the geochemical data.

4. Results

4.1. Stratigraphic Results

The surface of the Limbiko deposit is covered by ferruginous bauxites with a thickness of 1.7 - 3 m covered in some places with a plant soil. We have two types of bauxites in the Limbiko deposit: lateritic bauxites (*in situ*) and chemogenic bauxites [14] [15] [16] [17]. The former developed at the expense of clays, aleurolites and dolerites. The latter are derived from the chemical redistribution of the elements at the base of the lateritic bauxites, which are divided into two (2). Gelled bauxites have partially retained the textural and structural features of the parent rocks and gelomorphic bauxites that are fully transformed by the processes of redistribution and concentration of the aluminous substance [15].

The conventional boundary of the Limbiko Plateau geological formations (Figure 2 and Figure 3) is determined from exploratory drilling data (Figure 4). The study of stratigraphic logs A and B shows two types of formations: source rocks at the base (greater than 1 m) overlain by the weathering crust [20]. This weathering crust is characterized by four (4) zones [6] which are from bottom to top, the initial decomposition zone or saprolite (5 m thick)), the clay zone (4 to 6 m), the transition zone (1 to 4 m) and the free oxide or bauxite zone (8 m). This area of bauxite is represented by gelified bauxites and lateritic bauxites. Isolated intercalation of the sometimes nodular ferriplantites is observed (Figure 4).



Figure 3. Geological section along line A and B (this work). 1—Apodoleritic gelled bauxites; 2—Apodoleritic lateritic bauxites; 3—Lateritic bauxites derived from aleuro-argillites; 4—Bauxite laterites derived from aleuro-argillites; 5—Miocene station sedimentary lateritic formations covering Devonian rocks; 6—Clays; 7—Saprolites; 8—Rocks in place.



Figure 4. Stratigraphic logs of surveys A and B ([15]; modified by this work). 1—Vegetable soil; 2—Ferruginization zones; 3—Pseudomorphic gelled bauxites derived from dolerites; 4—Highly gelled pseudomorphic bauxites derived from dolerites; 5—Lateritic bauxites derived from aleuro-argillites; 6—Highly gelled bauxites derived from aleuro-argillites; 7—massive tobacco yellow ferriplantites; 8—Transition iron laterites with clay nests; 9—Tobacco yellow ferriplantite plates; 10—Pseudomorphic ferruginous red kaolinitic clays deriving aleuro-clays; 11—White, grayish-white and pink kaolinitic clays, pseudomorphs deriving aleuro-clays; 12—Polymineral clays with montmorillonite-kaolinite derived from dolerites; 13—Polymineral clays with hydromica-kaolinite gray pseudomorphs deriving aleuro-clays; 14—Saprolites derived from aleuro-argillites; 15—Saprolites derived from corneal aleuro-clays; 16—Aleuro-argillites.

4.2. Petrographic Results

Petrographic field and laboratory studies included bauxites, upper ferruginous laterites (cuirasses), transition zone ferruginous laterites, and ferriplantites.

4.2.1. Bauxites

The Limbiko deposit contains two (2) groups of bauxites which are:

Lateritic bauxites (*in-situ*) Two (2) litho-genetic types are distinguished according to the texturo-structural characteristics of lateritic bauxites:

- bauxites formed at the expense of aleurolites, Devonian clays (**Figure 5(a**)). These bauxites are most often referred to as structural bauxites;
- bauxites formed at the expense of Mesozoic dolerites (Figure 5(b)).

These two types of bauxites are characterized by their low quality and low aluminum monohydrate content, so gibbsite predominates. Alumogoethite has a low alumina content [21]. Titanomagnetite is generally found in apodoleritic bauxites, while rutile and anatase are typical for bauxites developed at the expense of Devonian rocks (Figure 5(a)). Lateritic bauxites are distinguished by their textural features and their division into plates for structural bauxites (Figure 5(a)), and in shells for apodoleritic bauxites (Figure 5(b)).

Chemical bauxites, represented by: 1) gelomorphic bauxites with relatively limited development in the deposit and 2) gelled bauxites which are widely distributed. They have a massive texture and an amorphous and microcrystalline structure [14] [15].

Texturally, gelled bauxites resemble lateritic bauxites, but differ from them in lighter pink, white pink and light beige.

In macroscopic terms, gelled bauxites formed at the expense of aleurolites and clays, and gelling generally appears through the blanching of the plates. This gelling leads to a lightening of the bauxites (Figure 5(c)).

In apodoleritic bauxites, gelling usually develops as alumogel nests of gibbsitic composition, dispersed in the bauxites, which leads to lightening of the ore (Figure 5(d)).

The bauxites gelled by their composition occupy an intermediate position between the gelomorphic bauxites and the lateritic bauxites.

Microscopically, bauxites derived from aleuro-clays are sometimes weakly ferruginous. The thin slats of these bauxites are listed in Figure 6(a) (lateritic bauxites) and Figure 6(c) (gelled bauxites).

In these thin slides, these bauxites have a cavernous pseudo-microbrechin texture. The fragments are colorless or pale yellow in a nicol (-) (Figure 6(a) and Figure 6(c)). The size of the fragments varies between 2 to 5 mm and 1.5 cm. Colomorphic clots usually appear in the microcrystalline gibbsitic mass. The size of the clot-shaped gelomorphic patches generally does not exceed 3 to 5 mm. The proportion of alumogel increases with increasing gelling of bauxites, more particularly in Figure 6(c).

Goethite is easily diagnosed in granular aggregates, in addition to ferruginous material, gibbsite crystal neoformations of 0.5 - 1 mm in size and secondary diaspora are encountered (Figure 6(a) and Figure 6(c)).



Figure 5. Bauxite samples. (a) Lateritic bauxites deriving from the aleuro-argillites; (b) Lateritic bauxites deriving from the dolerites; (c) Gelified bauxites deriving from the aleuro-argillites; (d) Gelified bauxites deriving from the dolerites.



Figure 6. Thin slats of bauxite samples under Polarized Light Not Analysed (-). Gbs: Gibbsite, Alg: Alumogoethite, Gth: Goethite, Hem: Hematite, Rt: Rutile, Kln: Kaolinite. (a) Lateritic bauxites deriving from the aleuro-argillites; (b) Lateritic bauxites deriving from the bauxites doleries; (c) Gelified bauxites deriving from the aleuro-argillites; (d) Gelified bauxites deriving from the dolerites.

In the thin slats of apodoleritic lateritic bauxites, the ophitic structure inherited from the original dolerites is often observed. In gibbsite crystals, chains of small, elongated, opaque hematite crystals are often observed, which most often show the trace of the macles of the original plagioclases (Figure 6(b)).

In the thin slats of apodolitic gelled bauxites (Figure 6(d)), there is a development in the slabs of alumogel and ferrialumogel. They have a collomorphic aphanitic structure. Generally, in the gelled varieties of apodolitic bauxites, the development of alumogel and crystalline gibbsite neoformations betray the residual appearance of the ophitic structure, which is difficult to see.

4.2.2. Ferruginous Laterities of the Upper Part of the Bauxitised Interval Ferruginous laterities (**Figure 7(a)** and **Figure 7(b)**) are bauxites derived from dolerites, which have a massive cavernous texture and an aphanitic collomorphic structure. They are composed in most cases of ferrigel and hematogel, forming ranges with rhythmic zonality lining the walls of cracks and caves. There are also large secondary gibbsite neoformation crystals with a size of 2 - 3 mm.

4.2.3. Ferruginous Laterites of the Transition Zone, Developed at the Expense of the Aleuro-Argillites of the Upper Limb of the Faro Suite

The ferruginous laterites (**Figure 8(a**)) have a pseudo-brechic texture, of yellowish red color presenting pores.

In the thin slat of **Figure 8(b)**, the size of the fragments varies between 0.1 and 0.8 cm, they are at sharp angles. The color of the fragments is very dark-red. The cement consists of hematogel and ferrigel with a yellow, yellowish-red color and is varied.

The fragments have a massive and collomorphic aphanitic texture. They are mainly composed (80% - 90% and more) of ferruginous minerals (goethite, hematite, etc.). The gibbsite forms a finely dispersive dissemination, and its content does not exceed 5% [15].

The cement is developed in the form of veins with an aphanitic texture and a collomorphic structure. In piercing light, the cement is semi-transparent. The nests are composed of microcrystalline gibbsite and kaolinite with thin slats of hydomuscovite. Venules on ferruginous beaches are composed of gibbsite and essentially gibbsite alumogel.

4.2.4. Ferriplantites

The tobacco-yellow ferriplantites have a massive or ribbon texture and a microcrystalline structure, rarely aphanitic columbite (**Figure 9(a)**). To these ferriplantites are attached the thin slats of **Figure 9(b)** taken from the laterites of the transition.

They consist essentially of a fine aggregate of crystals of goethite, gibbsite and kaolinite. Quartz grains of aleuritic dimension are also encountered locally. To-gether, gibbsite and kaolinite account for 10% - 15%.

In the yellow-tobacco ferriplantites of the transition zone (Figure 9(b)) are developed aluminous veins up to 3 mm in power and composed of alumogel or ferrialumogel. In places, they are transformed into gibbsite [15].



Figure 7. (a) Ferruginous laterites of the upper bauxitised interval; (b) Thin Slat in Polarized Light No Analyzed (PLNA). Gbs: Gibbsite, Alg: Alumogœthite, Gth: Gœthite, Hem: Hematite, Qz: Quartz.



Figure 8. (a) Iron-bearing silt of the transition zone; (b) Thin Slat Polarized Light No Analyzed (PLNA). Gbs: Gibbsite, Alg: Alumogoethite, Gth: Goethite, Hem: Hematite.



Figure 9. (a) Ferriplantites; (b) Thin Slat Polarized Light No Analyzed (PLNA). Alg: Alumogoethite, Kln: Kaolinite, Hem: Hematite.

4.3. Mineralogical Results

According to the results of the XRD analysis, the mineralogical composition is essentially similar in all the bauxites of Logs A and B. The results of the quantitative phase analysis are given in **Table 1** and **Table 2**. These values represent the relative amounts of crystalline and amorphous phases normalized to 100%. Not all samples contain boehmite and diaspora.

In Log A at the bauxite horizon, most samples contain gibbsite, alumogoethite, goethite, hematite, anatase and rutile which are accompanied by one or more combinations of mineral substances: kaolinite (A09 and A10); kaolinite, quartz (A03); kaolinite, quartz and hydromica (A10 and A12) (**Table 1**). In the clay horizon of Log A all samples contain kaolinite, quartz and hydromica. In

Table 1. Log A	mineralogical	test results.
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		Bauxitic horizon								Clay horizon									
Mineral	Chemical Formulas	A 1	A2	A3	A4	A5	A6	A7	A 8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18
Gibbsite	Al(OH) ₃	80	69	29	77	54	55	75	20	8	12	3	-	10	-	-	-	-	-
Boehmite	AlO(OH)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Diaspore	AlO(OH)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Alumogœthite, gœthite	FeO(OH)	9	9	14	9	5	5	7	10	33	14	22	5	21	9	-	-	-	-
Hematite	Fe ₂ O ₃	3	1	5	1	1	1	1	4	-	6	-	-	-	-	-	-	-	-
Anatase	TiO ₂	1	2	1	3	1	1	1	1	-	1	-	-	-	-	-	-	-	-
Rutile	TiO ₂	1	1	-	1	1	1	1	1	-	1	-	-	-	-	-	-	-	-
Kaolinite	$Al_2Si_2O_5(OH)_4$	-	-	3	-	-	-	-	-	4	15	7	65	5	45	30	15	10	5
Montmorillonite	$(Na, Ca)_{_{0,3}}$ (Al, Mg) ₂ Si ₄ O ₁₀ (OH) ₂ ·nH ₂ O	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Quartz	SiO ₂	-	-	3	-	-	-	-	-	-	3	-	5	2	3	22	23	20	28
Hydromica	(K, H ₃ O)(Al, Mg, Fe) ₂ (Si, Al) ₄ O ₁₀ [(OH) ₂ ·(H ₂ O)]	-	-	-	-	-	-	-	-	-	5	-	20	5	15	25	30	30	30
Chlorite	(Fe, Mg, Al) ₆ (Si, Al) ₄ O ₁₀ (OH) ₈	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-
Cordierite	$Al_3Mg_2AlSi_5O_{18}\\$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	5
Albit	NaAlSi ₃ O ₈	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2	2
Feldspah potassic	(Ba, Ca, Na, K, NH ₄) (Al, B, Si) ₄ O ₈	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Phase R/a		6	18	45	9	38	37	15	64	55	43	68	5	57	28	23	29	37	30

Table 2. Log B mineralogical test results.

		Bauxitic horizon								Clay horizon									
Mineral	Chemical Formulas	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18
Gibbsite	Al(OH) ₃	35	24	42	61	67	39	10	40	-	2	-	-	-	-	-	-	-	-
Boehmite	AlO(OH)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Diaspore	AlO(OH)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Alumogœthite, gœthite	FeO(OH)	14	17	11	8	7	7	5	5	-	17	5	-	-	-	-	-	-	-
Hematite	Fe_2O_3	4	6	1	2	2	2	20	4	-	5	2	-	-	-	-	-	-	-
Anatase	TiO ₂	1	1	1	1	1	1	1	1	-	1	-	-	-	-	-	-	-	-
Rutile	TiO ₂	1	-	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-
Kaolinite	$Al_2Si_2O_5(OH)_4$	-	-	-	-	-	-	-	3	48	5	48	40	35	35	20	10	20	5
Montmorillonite	$(Na, Ca)_{_{0,3}}$ (Al, Mg) ₂ Si ₄ O ₁₀ (OH) ₂ ·nH ₂ O	-	-	-	-	-	-	-	-	-	-	-	-	-	50	-	-	-	-
Quartz	SiO ₂	-	-	-	-	-	-	-	-	41	-	3	30	55	5	18	21	21	35
Hydromica	$(K, H_3O)(Al, Mg, Fe)_2$ $(Si, Al)_4O_{10}[(OH)_2 \cdot (H_2O)]$	-	-	-	-	-	-	-	-	8	2	20	25	10	-	25	40	35	15
Chlorite	(Fe, Mg, Al) ₆ (Si, Al) ₄ O ₁₀ (OH) ₈	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Continued																			
Cordierite	$Al_{\scriptscriptstyle 3}Mg_{\scriptscriptstyle 2}AlSi_{\scriptscriptstyle 5}O_{\scriptscriptstyle 18}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11	8	15
Albit	NaAlSi ₃ O ₈	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2
Feldspah potassic	(Ba, Ca, Na, K, NH_4) (Al, B, Si) $_4O_8$	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-
Phase R/a		45	52	45	28	23	51	63	46	-	68	22	5	-	10	37	18	14	28

addition to these minerals we note the presence of chlorite and albite in sample A16; Cordierite and albite in samples A17 and A18 (**Table 1**).

In Log B at the bauxite horizon, most samples contain gibbsite, alumogoethite, goethite and hematite which are accompanied by one or more mineral substances: rutile (B01 and B07); rutile and kaolinite (B08) (**Table 2**). In the clay horizon of Log B most samples contain kaolinite, quartz and hydromica, which are accompanied by one or more elements: Potassium feldspar (B09); cordierite and montmorillonite (B14); cordierite and albite (B17 and B18) (**Table 2**).

Based on the results of mineralogical analysis (Table 1 and Table 2), given the absence of boehmite and diaspora, we can say that gibbsite is the economic mineral of aluminum at the Limbiko Plateau.

4.4. Geochemical Results

Geochemical analysis shows that the Limbiko deposit is mainly composed of Al_2O_3 (11.24% - 57.64%), SiO_2 (0.04% - 70%), Fe_2O_3 (1.70% - 63.84%), TiO_2 (0.58% - 4.00%).

Alkali and alkaline earth: FeO (0.07% - 7.38%), CaO (0.02% - 0.72%), MgO (0.04% - 2.82%), MnO (0.01% - 0.35%), K₂O (0.00% - 4.30%), Na₂O (0.00% - 1.00%), P₂O₅ (0.00% - 0.60%) and PAF (3.02% - 31.26%) show values weak.

The clay (A12, A14, A15, B09, B11, B12, B13 and B14) and saprolitic (A16, A17, B16 and B17) samples have component values varying from: 16% - 35% Al₂O₃; 44.00% - 70.75% SiO₂; 1.70% - 13.20% Fe₂O₃; 1.10% - 2.10% TiO₂; 0.18% - 7.38% FeO; 0.05% - 0.72% CaO; 0.05% - 2.82% MgO; 0.01% - 0.35% MnO; 0.64% - 4.30% K₂O; 0.09% - 0.50% Na₂O; 0.01% - 0.6% P₂O₅ and 4.78% - 14.11% PAF.

Whereas the aleuro-argillites samples (A18 and B18) have respectively: 20.96% and 19.64% of Al_2O_3 ; 56.12% and 58.72% of SiO_2 ; 6.73% and 8.98% Fe_2O_3 ; 1.12% and 1.20% TiO_2 ; 6.10% and 6.57% FeO; 0.52% and 0.42% CaO; 1.98% and 2.17% MgO; 0.12% and 0.08% MnO; 4.10% and 4.00% K_2O ; 0.80% and 1.00% Na_2O ; 0.14% and 0.12% of P_2O_5 and 3.02% and 3.11% of PAF at the end (**Table 3**).

The mineralogical classification of Aleva [22] shows that most bauxitic samples (A02, A04, A05, A06, A07, A08, B03, B04, B05 and B06) of the Limbiko plateau fall into the bauxite and ferritic bauxite fields (**Figure 10**). Only A03 and B07 are in the laterite and bauxitic ferrite fields, respectively. The ferriplantite samples (A09, A11 and B10) and ferruginous laterites (A10 and A13) fall into the ferrite field. We also find that some clay samples (B11, B14 and B15) fall into

Table 3. Results of chemical analysis.

Gelified Bauxites										Later	teritic Bauxites Ferriplantites			tes						
N° Ech.	A1	A2	A3	A4	A5	A6	А	.7	A8	B1	B2	B3	B4	B5	B6	B7	B8	A9	A11	B10
Al ₂ O ₃ (%)	53.26	56.40	36.26	57.05	55.74	55.8	6 57.	.64 5	6.39	49.60	42.91	55.32	55.78	55.37	56.40	26.65	51.17	11.24	12.18	16.23
SiO2	0.78	0.20	8.64	0.31	0.46	0.64	l 1.0	00	1.04	0.63	0.35	0.04	0.04	1.00	1.95	1.00	4.65	9.20	13.88	21.00
Fe ₂ O ₃	13.38	7.18	30.87	8.42	9.96	9.92	2 7.4	41	9.03	18.71	26.75	10.46	10.83	10.05	8.25	51.05	12.80	63.84	58.23	46.90
TiO ₂	3.05	3.00	1.80	4.00	3.63	2.63	3 2.4	45 3	2.68	2.31	2.70	3.08	3.15	3.00	3.00	1.90	2.20	0.58	1.13	0.85
FeO	0.14	0.32	0.07	0.13	0.14	0.17	7 0.2	20	0.19	0.13	0.22	0.27	0.23	0.26	0.34	0.19	0.26	0.10	0.26	0.14
CaO	0.08	0.21	0.10	0.14	0.33	0.20	0.	11	0.13	0.14	0.38	0.10	0.23	0.05	0.05	0.30	0.05	0.18	0.08	0.05
MgO	0.10	0.14	0.10	0.15	0.30	0.14	ŧ 0.	11	0.13	0.09	0.15	0.09	0.12	0.07	0.09	0.06	0.09	0.13	0.08	0.19
MnO	0.02	0.02	0.07	0.02	0.03	0.03	3 0.0	03	0.03	0.04	0.03	0.05	0.03	0.05	0.05	0.02	0.03	0.01	0.02	0.34
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00) 0.0	00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00) 0.0	00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00) 0.0	00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PAF	29.24	31.26	22.42	30.20	30.22	30.6	8 31.	.14 3	0.80	28.18	25.62	30.28	30.12	30.03	30.00	17.07	29.67	14.46	14.54	13.50
	Ferrug	jinous L	aterites					Clays						Sapro	olites			Aleuro-	argillites	5
N° Ech.	A10		A13	A12	A14	A15	B9	B11	B12	B13	B14	B15	A16	A17	B16	B17	А	18	В	18
Al ₂ O ₃ (%)	23.71	1	20.64	35.30	28.45	21.13	22.91	24.63	25.62	18.43	18.80	16.00	20.71	21.85	21.20	19.85	20	.96	19	.64
SiO2	13.50)	9.70	44.37	46.25	62.50	64.27	45.50	60.38	70.75	46.25	57.12	55.62	56.60	58.00	57.50	56	.12	58	.72
Fe ₂ O ₃	46.74	4	49.50	4.63	7.70	4.30	1.70	13.20	2.62	1.92	15.12	9.76	5.45	4.04	6.36	6.74	6.	73	8.	98
TiO ₂	1.25		0.95	2.10	1.50	1.25	1.30	1.88	1.30	1.18	1.52	1.12	1.10	1.20	1.20	1.38	1.	12	1.	20
FeO	0.16		0.17	0.69	0.24	3.02	0.29	0.37	0.18	0.22	0.62	6.15	7.38	4.67	3.78	4.17	6.	10	6.	57
CaO	0.14		0.05	0.05	0.21	0.17	0.06	0.02	0.21	0.10	0.72	0.02	0.05	0.28	0.28	0.25	0.	52	0.	42
MgO	0.17		0.06	0.05	0.06	0.08	0.07	0.20	0.04	0.16	2.82	0.82	0.05	1.60	1.26	1.42	1.	98	2.	17
MnO	0.01		0.02	0.08	0.03	0.02	0.06	0.12	0.01	0.01	0.35	0.18	0.01	0.07	0.03	0.03	0.	12	0.	08
K₂O	0.00		0.50	2.18	4.00	3.67	3.55	3.17	3.33	1.64	0.64	2.73	3.67	4.00	4.00	4.30	4.	10	4.	00
Na ₂ O	0.00		0.10	0.10	0.27	0.22	0.15	0.24	0.29	0.10	0.09	0.20	0.21	0.50	0.29	0.37	0.	80	1.	00
P_2O_5	0.00		0.48	0.05	0.60	0.12	0.06	0.01	0.01	0.17	0.06	0.01	0.32	0.14	0.11	0.30	0.	14	0.	12
PAF	14.60	0	16.83	11.53	10.53	5.30	4.78	11.18	5.90	6.12	14.11	7.51	6.90	5.41	4.92	4.94	3.	02	3.	11

the kaolinite field, while other clays (A12, A14, A15, B09, B12 and B13), saprolites (A16, A17, B16 and B17) and aleuro-argillites (A18 and B18) fall into the kaolinite bauxite field (**Figure 10**).

The triangular diagram of degree of laterization of the bauxites of Schellmann [23] shows that the majority of the samples (A01, A02, A03, A04, A05, A06, A07, A08, A09, A10, A11, A13, B01, B02, B03, B04, B05, B06, B00 7, B08, B09 and B10) of Limbiko are strongly lateritized (Figure 11). Other samples (A12, A14, A15, A16, A17, A18, B09, B11, B12, B14, B15, B16, B17 and B18) are weakly laterized and one sample (B10) is at the boundary between high and moderate laterization. Only one sample (B13) is in the kaolinitization band (Figure 11).



Figure 10. Triangular diagram between Al₂O₃-Fe₂O₃-SiO₂ from [22].



Figure 11. Triangular diagram between Al₂O₃-Fe₂O₃-SiO₂ from Schellmann [23].

In the classification diagram of Boulange *et al.*, [24], all bauxite samples (A02, A03, A04, A05, A06, A07, A08, B02, B03, B04, B05, B06, B07 and B8) from the Limbiko deposit fall into the bauxite and ferruginous bauxite fields, except for one sample (B01) which is located between the two bauxite fields (Figure 12). The ferruginous laterites (A10 and A13) are between ferruginous bauxites and kaolinite. Ferriplantites (A09, A11 and B10) are located on either side of the kaolinitic line. Finally, the clays (A12, A14, A15, B09, B11, B12, B13, B14 and B15), the saprolites (A16, A17, B16 and B17) and the aleuro-argillites (A18 and B18) are in the kaolinitic field (Figure 12).

In the classification diagram of Beauvais [25] and Tardy [26], the geochemical pathways of dismantling indicate various trends followed during the bauxitization



Figure 12. Triangular diagram between Al₂O₃-Fe₂O₃-SiO₂ from Boulangé et al. [24].

process: kaolinite preservation, deferruginization, kaolinite destruction and dehydration (Figure 13). As well the clays, the saprolites and aleuro-argillites samples follow the kaolinite preservation trend. On the other hand, the samples of the ferruginous laterite are in the zone of ferruginous shadow. Finally, bauxite samples follow the trend of kaolinite destruction, indicating that the bauxites from the Limbiko deposit resulted from the destruction of kaolinite during the bauxitization process (Figure 13).

To study the behaviour of the elements, we established the correlation diagrams of SiO₂, Fe₂O₃ and TiO₂ as a function of Al_2O_3 , which are the main chemical elements.

The correlation diagrams of SiO₂, Fe₂O₃ and TiO₂ as a function of Al₂O₃ of Logs A and B are almost identical (**Figure 14**). The SiO₂ and Fe₂O₃ diagrams as a function of Al₂O₃ show that SiO₂ and Fe₂O₃ decrease when Al₂O₃ increases, indicating a negative correlation. This correlation is explained by the decrease in quartz, kaolinite, hydromica, hematite, goethite and alumogoethite and the increase in gibbsite contents. In contrast, TiO₂ versus Al₂O₃ diagrams show that TiO₂ increases with Al₂O₃ indicating a positive correlation. This positive correlation is explained by an increase in the rutile, anatase gibbsite contents (**Figure 14**) [18].

4.5. Statistics Results

4.5.1. Simple Linear Correlation or Bravais-Pearson Correlation of Logs A and B

The simple linear correlation coefficient, known as the Bravais-Pearson coefficient, is a normalization of the covariance by the product of the standard deviations of the variables. The correlation coefficient is independent of the units of measure of the variables, allowing comparisons. The measurement is normalized; it is defined between $-1 \le r \le 1$. When r = 1, the link between the parameters



Figure 13. Triangular diagram between Al₂O₃-Fe₂O₃-SiO₂ according to Beauvais [25] and Tardy [26].



Figure 14. SiO₂, Fe₂O₃ and TiO₂ correlation diagrams as a function of Al₂O₃.

is linear and positive perfect, that is to say the knowledge of X gives us the value of Y (and vice versa), if r = -1, the link is linear and negative perfect. These correlation coefficients measure the linear relationship strength between the variables.

Table 4 shows Bravais-Pearson correlations between each pair of variables. The numbers of pairs of data used to calculate these coefficients are shown in parentheses. The third number in each box of the table is the probability value that tests the statistical significance of the estimated correlations. Probability values below 0.05 indicate correlation coefficients significantly different from 0 at the 95.0% confidence level.

The study of these tables shows that the major elements have both perfect positive linear relationships (correlations and probability values increase in the same direction) with probability values below 0.05; And perfect negative linear relationships (correlations increase in the opposite direction of the probability values) with probability values less than 0.05.

	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	TiO ₂	FeO	CaO	MgO	MnO	K ₂ O	Na ₂ O	P ₂ O ₅
		-0.7238	-0.3378	0.9343	-0.4483	-0.1609	-0.3860	-0.3055	-0.5801	-0.4690	-0.3875
Al ₂ O ₃		(36)	(36)	(36)	(36)	(36)	(36)	(36)	(36)	(36)	(36)
		0.0000	0.0439	0.0000	0.0061	0.3484	0.0201	0.0700	0.0002	0.0039	0.0195
	-0.7238		-0.3988	-0.6778	0.6260	0.1860	0.4815	0.2178	0.9089	0.6846	0.4313
SiO2	(36)		(36)	(36)	(36)	(36)	(36)	(36)	(36)	(36)	(36)
	0.0000		0.0160	0.0000	0.0000	0.2776	0.0029	0.2019	0.0000	0.0000	0.0086
	-0.3378	-0.3988		-0.3192	-0.3153	-0.0825	-0.2053	0.0637	-0.4726	-0.3243	-0.0920
Fe_2O_3	(36)	(36)		(36)	(36)	(36)	(36)	(36)	(36)	(36)	(36)
	0.0439	0.0160		0.0577	0.0610	0.6324	0.2297	0.7120	0.0036	0.0537	0.5937
	0.9343	-0.6778	-0.3192		-0.4362	-0.0660	-0.3170	-0.2490	-0.5526	-0.4554	-0.4151
TiO ₂	(36)	(36)	(36)		(36)	(36)	(36)	(36)	(36)	(36)	(36)
	0.0000	0.0000	0.0577		0.0078	0.7022	0.0596	0.1430	0.0005	0.0053	0.0118
	-0.4483	0.6260	-0.3153	-0.4362		0.2410	0.5837	0.1111	0.7161	0.7658	0.3161
FeO	(36)	(36)	(36)	(36)		(36)	(36)	(36)	(36)	(36)	(36)
	0.0061	0.0000	0.0610	0.0078		0.1568	0.0002	0.5190	0.0000	0.0000	0.0604
	-0.1609	0.1860	-0.0825	-0.0660	0.2410		0.7701	0.3035	0.1808	0.4369	0.0518
CaO	(36)	(36)	(36)	(36)	(36)		(36)	(36)	(36)	(36)	(36)
	0.3484	0.2776	0.6324	0.7022	0.1568		0.0000	0.0719	0.2914	0.0077	0.7643
	-0.3860	0.4815	-0.2053	-0.3170	0.5837	0.7701		0.5106	0.4502	0.6904	0.1378
MgO	(36)	(36)	(36)	(36)	(36)	(36)		(36)	(36)	(36)	(36)
	0.0201	0.0029	0.2297	0.0596	0.0002	0.0000		0.0015	0.0059	0.0000	0.4229
	-0.3055	0.2178	0.0637	-0.2490	0.1111	0.3035	0.5106		0.0328	0.1106	-0.1181
MnO	(36)	(36)	(36)	(36)	(36)	(36)	(36)		(36)	(36)	(36)
	0.0700	0.2019	0.7120	0.1430	0.5190	0.0719	0.0015		0.8494	0.5209	0.4928
	-0.5801	0.9089	-0.4726	-0.5526	0.7161	0.1808	0.4502	0.0328		0.7960	0.5327
K ₂ O	(36)	(36)	(36)	(36)	(36)	(36)	(36)	(36)		(36)	(36)
	0.0002	0.0000	0.0036	0.0005	0.0000	0.2914	0.0059	0.8494		0.0000	0.0008
_	-0.4690	0.6846	-0.3243	-0.4554	0.7658	0.4369	0.6904	0.1106	0.7960		0.3721
Na ₂ O	(36)	(36)	(36)	(36)	(36)	(36)	(36)	(36)	(36)		(36)
	0.0039	0.0000	0.0537	0.0053	0.0000	0.0077	0.0000	0.5209	0.0000	0.0501	0.0255
ЪО	-0.3875	0.4313	-0.0920	-0.4151	(20)	0.0518	0.1378	-0.1181	0.5327	0.3721	
P ₂ O ₅	(36)	(36)	(<i>3</i> 6) 0 5937	(36)	(36)	(36) 0.7643	(36)	(36)	(36)	(36)	
	0.0193	0.0080	0.393/	0.0118	0.0004	0.7043	0.4229	0.4928	0.0008	0.0200	

Table 4. Bravais-pearson correlations.

Correlation (Significant correlation); (Sample size); Probability (Confidence probability).

4.5.2. Principal Component Analysis (PCA)

The purpose of this analysis is to obtain a small number of linear combinations of the 11 variables that take into account most of the data variability. In this case, 3 components were extracted (**Table 5**), as these components have eigenvalues greater than or equal to 1.0 (**Figure 15**). Together they account for 79.418% of the variability of the original data.

1) Weight of variables

To obtain the weights of the variables, their values should be standardized by subtracting the respective averages and dividing by the respective standard deviations.

Table 6 displays the principal component equations:

- $CP1 = +0.380196*SiO_2 + 0.354755*FeO + 0.389711*K_2O + 0.410141*Na_2O;$
- $CP2 = +0.476754^{*}Al_{2}O_{3} + 0.473488^{*}TiO_{2} + 0.274324^{*}MnO;$
- $CP3 = +0.508774*Fe_2O_3 + 0.335531*CaO + 0.359017*MgO 0.417911*P_2O_5.$

Table 6 shows us that component 1 has a positive correlation with SiO_2 , FeO, K_2O and Na_2O , which indicates that component 1 would be composed of quartz, hydromica, kaolinite, albite and goethite. Component 2 has a positive correlation with Al_2O_3 and TiO_2 and a moderate positive correlation of MnO, so it would be composed of gibbsite, anatase and rutile. Finally, component 3 has a strong positive correlation with Fe_2O_3 , CaO and MgO and a negative correlation with P_2O_5 , so it would be composed of hematite, chlorite and cordierite.

The diagram of components 1, 2 and 3 of the distribution of samples according to major elements (Figure 16) shows three (3) groups of samples (clay, bauxite and ferrite).

The samples (A12, A14, A15, A17, A18, B09, B11, B12, B13, B14, B15, B16, B17 and B18) correlate with component 1 which shows that they are clayey. While samples (A01, A02, A03, A04, A05, A06, A07, A08 B01, B02, B03, B04, B05, B06, B07 and B08) correlate with component 2, which could correspond to bauxites. Finally, the samples (A09, A10, A11, A13 and B10) correlate with component 3, so they could be ferrites.

4.5.3. Hierarchical Classification (Clustering)

This procedure created a class based on the 36 observations entered. Classes (clusters) are groups of observations that have similar characteristics. To form classes, the procedure begins with each observation in a separate group. It then combines the two closest observations into a new group. After recalculating the distances between the groups, the next two closest groups are combined. This process is repeated until only one group remains. The resulting diagram is called a dendrogram.

Analysis of the dendrogram of the 36 samples of bauxites, ferrites, clays, saprolites and aleuro-clays from Logs A and B (Figure 17) generated six (6) classes convincingly, indicating relatively high interdependence. Class 1 displays the lowest link distance and consists of fourteen (14) samples (A01, A02, A03, A04, A05, A06, A07, A08, B01, B03, B04, B05, B06 and B08), all bauxitic and collected

Component number	Own values	Variance percentage	Cumulated percentage
1	5.17018	47.002	47.002
2	1.85396	16.854	63.856
3	1.7118	15.562	79.418*
4	0.820141	7.456	86.873
5	0.616322	5.603	92.476
6	0.416784	3.789	96.265
7	0.190016	1.727	97.993
8	0.105161	0.956	98.949
9	0.0744589	0.677	99.626
10	0.0402006	0.365	99.991
11	0.000981048	0.009	100.000

Fable 5. Logs A	and B main	component Analysis.
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Figure 15. Chart of own variables.

Table 6	Variable	weight table.
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	Component 1	Component 2	Component 3
Al ₂ O ₃	-0.243701	0.476754	-0.213033
SiO ₂	0.380196	-0.112045	-0.237427
Fe ₂ O ₃	-0.125053	-0.456631	0.508774
TiO ₂	-0.23885	0.473488	-0.194114
FeO	0.354755	0.0148735	-0.134032
CaO	0.241883	0.329432	0.335531
MgO	0.329449	0.241558	0.359017
MnO	0.27018	0.274324	0.26362
K ₂ O	0.389711	-0.0344759	-0.303615
Na ₂ O	0.410141	0.102295	0.0771221
P ₂ O ₅	0.193368	-0.271007	-0.417911

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Figure 16. Biplot.



Figure 17. Sample dendrogram.

between 0 and 12.5 meters' depth. Class 2 consists of five (5) samples (A09, A10, A11, B02 and B07), all of which are bauxitic, and are collected between 12.5 and 15 meters deep. Class 3 consists of nine (9) samples (A12, B11, B09, B12, B13, A15, A17, B16, B17) all clayey and saprolite, all from 15 to 21 meters' depth. Class 4 includes two (2) samples (A18 and B18) that are aleuro-argiilite, sampled between 21 and 23 meters deep. Class 5 comprises five samples (A16, B15, A14, A13, A10) and finally Class 6 comprises one sample (B14) all taken from 15 to 25 m of depth.

Analysis of the dendrogram of the 11 major elements of the Logs (Figure 18) shows that elements with similar behaviours are grouped into the same class. The analysis generated two classes with different binding distance. Class 1 shows the lowest connecting distance and comprises four elements which are: Al_2O_3 , TiO_2 , Fe_2O_3 and MnO. The Class 1 elements are all lithophilic except Fe, which is siderophilic according to the Goldschmid (1920) chemical classification and has been concentrated in iron minerals. Al_2O_3 and TiO_2 are immobile elements during the alteration process. Class 2 consists of seven elements: SiO_2 , K_2O , CaO,



Figure 18. Dendrogram of chemical elements.

FeO MgO, P_2O_5 , and these are mobile elements during the alteration process. K, Mg, Ca are lithophilic, Fe are sideropilic and S is chalcophile.

5. Discussions

Gibbsite, boehmite and diaspore are the main minerals in aluminum. Gibbsite $Al(OH)_3$ is one of the most common mineral species and those most readily seen in bauxites [27]. The gibbsitic bauxites, essentially Tertiary or younger [6], are found mainly in a tropical region characterized by a hot and humid climate [3]. Diaspora has been found as a minor component in several types of bauxite in which it is accompanied by gibbsite and boehmite [28] suggested that diaspora is the stable phase under the surface under climatic conditions and that gibbsite and boehmite are metastable, the presence of which is largely due to slow transformations. Alumogoethite, found in many bauxite deposits, is a substitute for Al_3^+ by Fe_3^+ in goethite and soil [29].

The geochemical trajectories of Beauvais [25] and Tardy [26] dismantling of lateritic bauxites from Limbiko bauxites suggest that bauxite is the product of the destruction of kaolinite. For example, indirect bauxitization or the desilication of kaolinite [9] in a hot and humid tropical climate [3] is the main mechanism for altering the formation of Bauxite gibbsites in the Limbiko Plateau.

Schellmann's degree of lateritization [23] shows the degree of bauxitization. Thus bauxitic samples are strongly laterized [6] [30] or mild lateralization [31] [32], while clayey are weakly lateritized [32] see kaolinitised (this work).

In the Aleva [22] diagram, bauxite samples are generally in the bauxite, kaolinitic and ferritic bauxite fields [31] [32], ferritic samples in bauxitic ferrite, ferrite, kaolinitic ferrite fields ([6]), clay samples in kaolinitic, bauxitic kaolinitic and ferritic kaolinitic fields [31] [32], laterite clay bauxites in the laterite field.

In the Boulangé *et al.* [24] classification, bauxitic samples are generally in the bauxite and ferruginous bauxite fields [6].

Correlation analysis (**Table 4**) showed a positive correlation between Al_2O_3 and TiO_2 and a negative correlation between SiO_2 and Al_2O_3 ; Fe_2O_3 and Al_2O_3 in bauxite. This is due to Si leaching, migration and accumulation of iron to form ferrites, and residual enrichment of aluminum and titanium during the alteration process [31]. High titanium oxide values are likely related to the abundance of minor Ti minerals (rutile, anatase) in bauxites. While elevated iron values in bauxite samples are related to the presence of iron-containing minerals such as hematite, goethite and alumogoethite, formed under appropriate Eh-PH conditions during the alteration process [32].

The hierarchical classification shows interdependence between Al and Ti [33], this may result from the direct relationship of the deposits with the clay component of the Limbiko aleuro-clays or that TiO_2 and Al_2O_3 were concentrated in highly altered horizons [34]. Ti and Al were immobile during the bauxitization process.

MacLean *et al.*, [35] have suggested that stationary elements are useful for tracking aluminum to a particular rock type.

6. Conclusion

In sum, petrological and statistical studies show that the Limbiko bauxite deposit has, on the one hand, a Devonian aleuro-argillite and Mesozoic dolerite origin; and, on the other hand, a chemogenic origin resulting from the chemical redistribution of elements underlying the lateritic bauxites. The mineralogical composition is marked by the presence of gibbsite, goethite, alumogoethite and the absence of diaspora, and boehmite in the bauxitic horizon; the clayey horizons are characterized by kaolinite, quartz and hydromica. One also notes the presence of minor minerals (anatase, rutile, montmorillonite, chlorite, albite cordierite, potassium feldspar). The geochemistry of the major elements allowed us to affirm on the one hand that the bauxite of Limbiko follows the destructive tendency of kaolinite during the bauxitization process and on the other hand that the bauxites, the ferruginous laterites, the ferriplantites are strongly lateritized, whereas the clays, the saprolites and the aleuro-argillites are weakly lateritized. It can be seen that as the quartz, kaolinite and hematite contents decrease, the gibbsite content increases, conversely the rutile, anatase and gibbsite contents increase in the same direction. The results of the statistical analysis confirm the result of the mineralogy by grouping all the samples in three batches (clay, bauxite and ferrite).

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Conflicts of Interest

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

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