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Andosolization of Soils on a Strombolian Cone at Mount Bambouto, Cameroon

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ABSTRACT

Morphology, mineral and geochemical investigations were carried out on two selected soil pedons (ZA and TO) developed on a late Quaternary-aged strombolian cone to better understand andosolization processes in Mount Bambouto, Cameroon. Both pedons have A-BC-C horizonation. They have thick surface (A) horizon with bulk density <0.7 g·cm^{-3}, $Al_o + 0.5Fe_o$ about 2% and P retention $>90\%$. Mineral association consists predominantly of kaolinite, gibbsite, goethite, organometal complexes and trace amount of ferrihydrite and allophane. The Ki values between 1.1 and 1.6, the low TRB (45 to 67 mg·kg^{-1}), the important IMob (20% to 24%), the CIA between 60% and 70% and the EFs above 1.16 for Al and Fe, and below 0.6 for Si indicate sparingly hydrolysis process in subsoil during which released Al, Fe and Si form allophanic or ferrihydrite minerals undergo crystallization into kaolinite, gibbsite and goethite, respectively. At topsoil, part of released Al (and Fe) is organically bounded with organic acids to form organometal complexes.

Keywords: *Soil Morphology, Mineralogy, Geochemistry, Andosolization, Strombolian Cone, Cameroon Volcanic Line*

1. Introduction

The Cameroon Volcanic Line extends 1600 km from the Gulf of Guinea (island of Pagalu) into western Cameroon. Volcanic activity principally ranged from Tertiary to Quaternary in age, but is still on-going [1,2]. Mount Bambouto is a strato-volcano with a well-preserved collapse caldera that has developed from multiple volcanic events initiating with thick basalt lava flow sequences, followed by an eruption with trachytic (fine-grained alkali intermediate igneous rocks) lava flows, with other subsequent volcanic eruptions [1,3]. These volcanic deposits cover an area of about 500 km[2] intensely used for annual crops and vegetable production. Soil survey of Mount Bambouto, documented soils with andic properties [4] above 1700 m asl that are formed under a wet, humid climate. Several studies related to pedogenesis have been conducted on soils developed from both trachytes [5,6] and basaltic rocks [7] dated between 16 and 4.5 Ma [1,3,8]. These studies showed that Andosols occur on both parent materials.

The andosolization process involves the rapid weathering of fine-grained parent rocks containing glass and microlites under humid conditions. In old trachytes and basaltic rocks from Mount Bambouto, this weathering commonly results in the formation of stable organometal complexes at the soil surface [6]. They are thus non allophanic Andosols and classify as Aluandic Andosols (leptic) based on the WRB system of soil classification [4]. Shoji *et al.* [9] reported that non allophanic Andosols show very strong acidity (pH < 5.0), high Al saturation and subsequent toxicity of Al to plants. They have horizons with Si_o less than 0.6%, Al_p/Al_o ratio above 0.5 in the top horizon and phosphorus retention more than 70%. The major occurrences of Andosols in Africa are found in the Rift valley, in Kenya, Rwanda and Ethiopia and in Madagascar [10]. In Cameroon, they occur around Mount Cameroon stretching through the Bakossi area (Mount Manengouba) to Loum and Nkongsamba areas, in Foumbot and in Mount Bambouto (West region), in Wum (North West region), and in the Adamawa plateau [11,12].

However, a recent geological review of Mount Bambouto reported the presence of a strombolian cone made of late quaternary (Middle Pleistocene) basaltic clasts on the NE slope of this mountain that dated around 0.480 ± 0.014 Ma [13]. This finding brought up a question about the andosolization process in Mount Bambouto, and the source of Al (and Fe) involved in the formation of organometal complexes in topsoil is also questioned. Al-

though it is well-known that the physico-chemical composition of the parent rock is one of the main factor controlling andosolization, Tematio *et al.* [6] mentioned that Al and Fe involved in organometal complexes in Mount Bambouto may originate from partial hydrolysis of secondary minerals (halloysite and iron oxides) due to high microbial activities [14] with liberation of metals which bond to organic acids [15]. This explanation is proved to be acceptable for soils derived from old trachyte [15]. This is what motivated the current research on morpho-chemical characterization of soils derived from the recent strombolian cone. The objectives of the study were thus to: 1) evaluate and quantify the andosolization mechanism prevailing on recent strombolian cone in Mount Bambouto by identifying the source of Fe and Al involved in the process; and 2) assess the weathering process and intensity operating in this environment as compared to andosolization process on ancient trachytic lava flows.

2. Materials and Methods

2.1. The Site Setting

Mount Bambouto is one of the major volcanic mountains in the Cameroon volcanic line that crosses the western part of the area. It is made up of various volcanic products

grouped into basic (alkali basalt, basanite, mugearite, hawaïte) and highly differentiated (trachyte, phonolite, rhyolite, ignimbrite) rocks [1-3]. A recent geological review [13] reports a late quaternary (Middle Pleistocene) strombolian cone in the NE slope of Mount Bambouto (**Figure 1**). This strombolian cone consists of basaltic clasts with hyalo-microlitic and porphyritic texture. Mineral paragenesis is spinel, olivine, Ti-magnetite, clinopyroxene, plagioclase, leucite and interstitial glass with nepheline to sodic plagioclase composition. According to their silica (SiO_2: 41.9% - 43.3%) and alkaline (MgO: 12.4% - 12.7%; CaO: 10.5% - 11.4%; Na_2O: 2.1% - 3.0% and K_2O: 0.9% - 1.2%) contents, and their normative composition (6.3 < nepheline w% < 10.7; 24.2 < olivine w% < 24.8), they belong to basanite from sodic series [13].

The NE slope of Mount Bambouto is characterized by wet, humid and cool climate with perudic moisture regime (1700 to 1800 mm annual rainfall) and isothermic conditions (15°C to 18°C mean annual temperature). The rainy season stretches from March to October and the drying season from November to February. The land use in this area consists of annual row cropping with rotational farming of maize, bean, potatoes, etc.
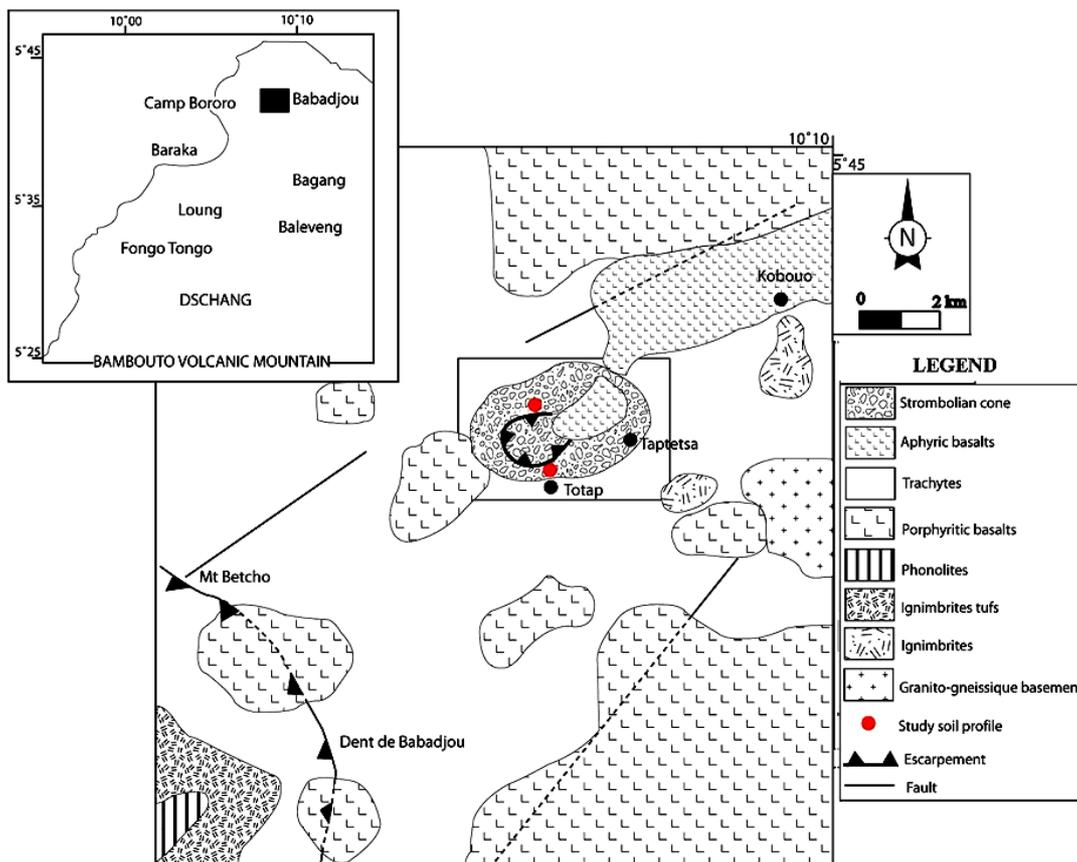

Figure 1. Geological scheme of the study area.

2.2. Methods

Two soil profiles were selected for the study on the late quaternary-aged deposits: the ZA pedon located at an elevation of 1925 m asl in the northern slope of the cone, and the TO pedon at 2005 m asl in the southern slope of the cone (**Figure 1**). Soil profiles were exposed by hand dug pedons through the soil and into the unweathered parent material. Profiles were differentiated by horizon and a morphological description was made [16], consisting of soil color, texture, structure, consistence, and horizon boundary. In each profile, soil samples were collected in triplicate along the thickness of each horizon and mixed to obtain a mean sample. Samples were air-dried, crushed (for saprolite samples), and sieved to the <2 mm fraction prior to physical, mineral and chemical analyses.

Previously, the bulk density (BD) is obtained by the cylinder method using BD = w/v formula where w is the weigh of soil contained in the cylinder and v its volume. Particle size was performed by the Robinson pipette method with Na hexametaphosphate as dispersal agent. Organic matter is previously oxidized using di-ionized water (H_2O_2). Organic carbon (OC) is obtained by oxidation using potassium dichromate as oxidizing agent. The available P is extracted by the combination of HCl and NaF, and quantified using ammonium molybdate with ascorbic acid as reducing agent. CEC and exchangeable cations are extracted by ammonium acetate ($CHOONH_4$) at pH 7 and quantified using atomic adsorption spectrometer (AA spectrometer). P retention was performed by colorimetry with nitric acid reagent, and quantified by spectrophotometer.

X-ray diffraction (XRD) was performed in finely ground samples using a Rigaku Geigerflex X-ray diffractometer operating at 40 kV and 45 mA with a Dmax-B controller and Cu Kα radiation. Samples were analyzed from 3° to 75° 2θ, at 1° 2θ/min. Relative amounts of minerals were assessed using peak height above background assuming that intensity (counts/s) of the highest peak of a mineral corresponds to 100% of this mineral in the sample. Selective dissolutions [17] were performed using acid ammonium oxalate, dithionite-citrate (DC) and Na pyrophosphate, identified here by the subscripts "o", "d" and "p", respectively. Extractable Si, Al and Fe were quantified by plasma emission spectroscopy using a JY24 ICP-OES spectrometer. Allophane was estimated by 7.1 x Si_o [18]. Ferrihydrite was estimated by $1.7 \times Fe_o$ [19] and goethite by $[1.6 \times (Fe_d - Fe_o)]$ [20].

Elemental analysis of the soil was performed following dissolution of the material in concentrated HNO_3, HCl and HF acids. Selected elements (Si, Al, Fe, Ti, Ca, Mg, K, Na, Mn, P) were quantified by inductively-coupled plasma spectrometry (ICP-AES). Mass content of each analysed element is reported on a percent oxide basis. En-

richment factor (EF) was estimated by the ratio between content of an element in soil material and that of the fresh rock according to the relation EF(X) = (Xi/Ri)/(Xs/Rs) [21], in which Xi and Ri are the concentrations of the element of interest and a reference element (Ri) in a given horizon and Xs and Rs are the concentrations of the same elements in the rock. The total reserve in bases (*TRB*) represents the sum of base cations (Ca + Mg + K + Na) from the total analysis, expressed as $mg \cdot kg^{-1}$ of soil [22]. The chemical index of alteration (*CIA*) corresponds to $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where CaO* is the amount of CaO incorporated in the silicate fraction of fresh rock while Na_2O, K_2O and Al_2O_3 are their concentrations in the analysed soil samples [23]. The mobility index of element (*IMob*) is $[(Mob_{rock} - Mob_{soil})/(Mob_{soil})] \times 100$ with *Mob* equal to $(K_2O + CaO + Na_2O)$ [24].

3. Results

3.1. Soil Morphology

The two soil pedons (ZA and TO) (**Figure 2**) have relatively shallow, weathered (A-BC-C) profiles with thick surface horizons (**Table 1**). In ZA pedon, the A horizon is 52 cm thick and consists of very dark grey (5YR3/1) silty clay, with fine to very fine crumb structure, and friable to very friable consistence. Its lower boundary is diffuse and irregular. It grades to the underlying brighter colored BC horizon. This BC horizon consists of light yellow brown (2.5Y6/4) weathered saprolite fragments
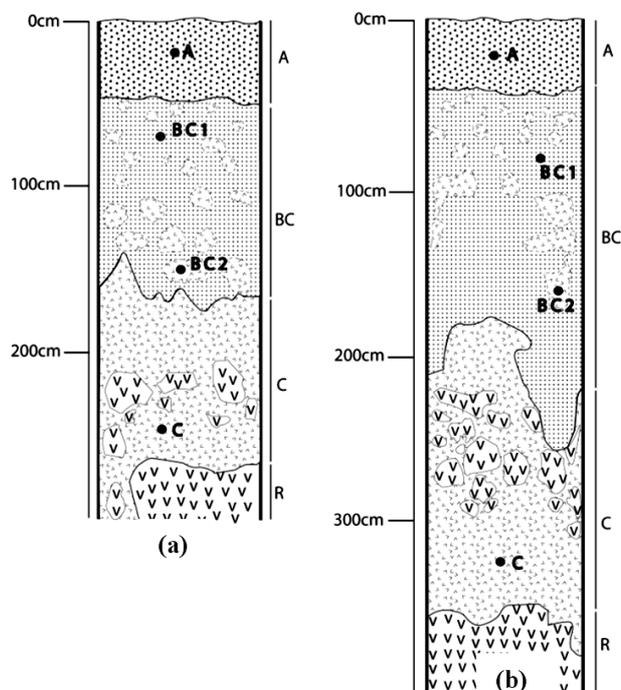

Figure 2. Morphological representation of: (a) ZA; and (b) TO soil pedons.

Table 1. Morphological characteristics of the selected pedons.

Pedon	Horizon	Samples	Depth (cm)	Color	Textural classes	Structure	Consistence	Lower boundary	Rock fragments (size and volumetric percentage)
ZA pedon	A	A	0 - 52	5YR3/1	sc	very fine crumble	friable to very friable	diffuse and irregular	-
	BC	BC1	52 - 160	7.5YR4/4	sc	granular	firm	distinct and abrupt	-
		BC2		2.5Y6/4	sc	massive	-		5 cm - 20cm 2% - 20%
	C	C	160 - 260	7.5YR7/4 to 2.5Y6/2	ss	massive	-	-	-
TO pedon	A	A	0 - 44	5YR3/4	sc	fine to coarse crumble	very friable	diffuse and irregular	-
	BC	BC1	44 - 206	7.5YR4/4	ss	fine granular	firm	distinct and abrupt	-
		BC2		10YR5/3 2.5Y6/2	ss*	massive	-		5 cm - 25cm 5% - 20%
	C	C	206 - 360	10YR5/3	ss*	massive	-	-	-

Textural classes: sc, silty clay; ss, silty sand; ss*, sandy silt.

with micrometric and polychromatic punctuations embedded in a dark brown (7.5YR4/4) silty clay soil matrix. It has fine granular soil structure with firm consistence. There are also a few unweathered pyroclastic fragments. With depth, weathered saprolite fragments become bigger and form a continuous C horizon below 2.0 m.

The boundary of the BC horizon with the underlying C-horizon is distinct, with an abrupt, wavy boundary. This C horizon consists of pink (7.5YR7/4) to light brown grey (2.5Y6/2) silty sand weathered materials with micrometric and polychromatic punctuations.

Pedon TO is 3.6 m deep. The A horizon is 44cm thick, dark brown (5YR3/4) colored, silty clay texture with fine to coarse crumb structure and very friable consistence. Its transition to the underlying brighter colored BC horizon is gradual, with a diffuse and irregular boundary.

The fine earth of BC horizon is dark brown (7.5YR4/4), silty sand texture with fine granular structure and firm consistence. It has weathered saprolite fragments that are light brown (10YR5/3) and break down into a sandy silt texture, and few light brownish grey (2.5Y6/2) unweathered pyroclastic fragments. With depth, the weathered saprolite and unweathered pyroclastic fragments increase in number and size and demarcate an almost continuous C horizon at about 1.5 m depth. The transition to the underlying C horizon is distinct, with an abrupt and irregular boundary.

3.2. Physico-Chemical Soil Properties

The bulk density (**Table 2**) is very low (<0.82 g·cm^{-3}) throughout the profiles of both soils, with values of 0.65 g·cm^{-3} and 0.67 g·cm^{-3} in surface horizons of pedons ZA and TO, respectively, and increasing slightly with depth. Particle size indicates moderate proportion of sand at the

soil surface (≈35%) which increases up to about 75% with depth. Inversely, the amount of clay is high at soil surface (39% and 29%, for pedons ZA and TO, respectively) and decreases significantly in the C horizons (<8%). The amount of silt also decreases slightly with depth.

The soils ranges from highly-acid to acid, with pH ranging from 4.3 to 5.3 in pedon ZA and 3.9 to 4.7 in pedon TO. The organic carbon is very high in the surface horizon (7.0% and 5.9% in pedons ZA and TO, respectively). The available P is also relatively high at soil surface (11 mg·kg^{-1} and 7 mg·kg^{-1} in pedons ZA and TO, respectively). The sum of exchangeable cations is low (less than 12 cmol·kg^{-1}), with its highest values deeper in the profile. The most abundant exchangeable cations are Mg^{2+} (≤7.7 cmol·kg^{-1}) and Ca^{2+} (≤3.2 cmol·kg^{-1}). Inversely, the CEC is relatively high (19.6 to 28.9 cmol·kg^{-1} in pedon ZA and 20.1 to 25.4cmol·kg^{-1} in pedon TO). The exchangeable Al^{3+} is relatively low in pedon ZA, but ranges up to 11.3cmol·kg^{-1} in pedon TO. The P retention is very high, >90% in the upper part of both soils. The acid ammonium oxalate extractable $Al_o + 0.5Fe_o$ is about 2% at soil surface, but decreases with depth.

3.3. Soil Mineralogy

In general, mineral associations in the studied soils correspond to kaolinite, gibbsite, goethite, ferrihydrite, allophane and organometal complexes. However, primary minerals like plagioclase and pyroxene are still present in specific materials. Both soils contain a large amount of organometal complexes (**Tables 3** and **4**) as well as short-range and long-range ordered minerals. There are also not completely weathered primary minerals remaining in these soils.

***The primary minerals*:** Primary minerals include plagioclase and pyroxene (**Figure 3**). In pedon ZA, plagioclase

Table 2. Physical and chemical soil properties of the selected pedons.

Studied pedon	Soil horizon	samples	BD (g·cm⁻³)	Particle size (%)			pHw	Organic matter		Exchangeable cations (cmol·kg⁻¹)						CEC (cmol·kg⁻¹)	P retention (%)	$Al_o + 0.5Fe_o$ (%)
				clay	silt	sand		OC (%)	available P (mg·kg⁻¹)	Ca^{2+}	Mg^{2+}	K^+	Na^+	S	Al^{3+}			
ZA pedon	A (0 - 52 cm)	A	0.65	31	31	38	4.3	7.0	11	2.2	0.8	0.1	0.0	3.1	1.5	27.1	94	1.9
	BC (52 - 160 cm)	BC1	0.75	39	27	34	4.5	0.48	1	0.3	1.2	1.0	0.0	2.5	1.5	22.2	92	1.7
		BC2	0.77	38	26	36	5.3	0.15	0	1.1	1.8	0.4	0.0	3.3	0.5	19.6	93	1.6
	C (160 - 260 cm)	C	0.81	7	18	75	4.9	0.0	7	1.7	7.6	0.1	0.0	9.4	0.5	28.9	83	1.2
TO pedon	A (0 - 44 cm)	A	0.67	29	38	33	4.7	5.9	7	2.3	1.0	0.1	0.0	3.4	4.5	25.4	95	2.2
	BC (44 - 206 cm)	BC1	0.66	20	24	56	3.9	1.1	0	1.0	1.7	0.1	0.0	3.4	7.0	23.1	92	1.3
		BC2	0.75	6	20	74	3.9	0.0	7	1.1	3.0	0.1	0.0	4.2	11.3	20.1	75	0.8
	C (206 - 360 cm)	C	0.72	4	18	78	4.4	0.0	5	3.2	7.7	0.2	0.0	11.1	1.3	22.3	78	1.1

OC: organic carbon; S: sum of exchangeable cations; BD: bulk density.

Table 3. Selective extraction data for selected pedons.

Selected pedon	Soil horizon	samples	Total concentration		Selective extraction						
					concentrations in %						
			Al_T	Fe_T	Al_d	Fe_d	Al_o	Fe_o	Si_o	Al_p	Fe_p
ZA pedon	A (0 - 52 cm)	A	11.01	13.64	1.30	8.90	1.18	1.39	1.88	0.80	1.20
	BC (52 - 160 cm)	BC1	12.07	13.64	1.40	9.10	0.93	1.57	1.72	0.90	0.60
		BC2	12.01	13.78	1.00	9.0	0.72	1.71	1.58	0.30	0.40
	C (160 - 260 cm)	C	10.43	15.32	0.50	7.50	0.50	1.37	0.69	0.10	-
TO pedon	A (0 - 44 cm)	A	10.58	13.50	1.30	8.40	1.31	1.68	2.15	0.80	0.60
	BC (44 - 206 cm)	BC1	11.85	13.15	0.90	7.90	0.69	1.26	1.32	0.30	0.30
		BC2	11.59	9.72	0.50	4.10	0.48	0.62	0.79	0.20	-
	C (206 - 360 cm)	C	10.74	13.57	0.40	7.70	0.42	1.25	1.07	0.10	-

Table 4. Minerals in the selected pedons.

Pedon	Soil horizon	samples	Minerals detected by XRD				Minerals estimated by selective extraction			
			abundance in %							
			kaolinite	gibbsite	plagioclase	pyroxene	goethite	ferrihydrite	allophane	Organo-metal complexes
ZA pedon	A (0 - 52 cm)	A	71	12	0	-	12	2.4	1.1	2.1
	BC (52 - 160 cm)	BC1	57	26	0	-	12	2.7	0.6	0.9
		BC2	54	29	0	-	12	2.9	0.9	0.7
	C (160 - 260 cm)	C	60	13	14	-	10	2.3	1.1	0.1
TO pedon	A (0 - 44 cm)	A	75	9	0	0	11	2.9	1.1	1.4
	BC (44 - 206 cm)	BC1	29	19	23	0	11	2.1	0.7	0.6
		BC2	3	3	64	23	6	1.1	0.6	0.2
	C (206 - 360 cm)	C	29	0	57	0	10	2.1	0.9	0.1

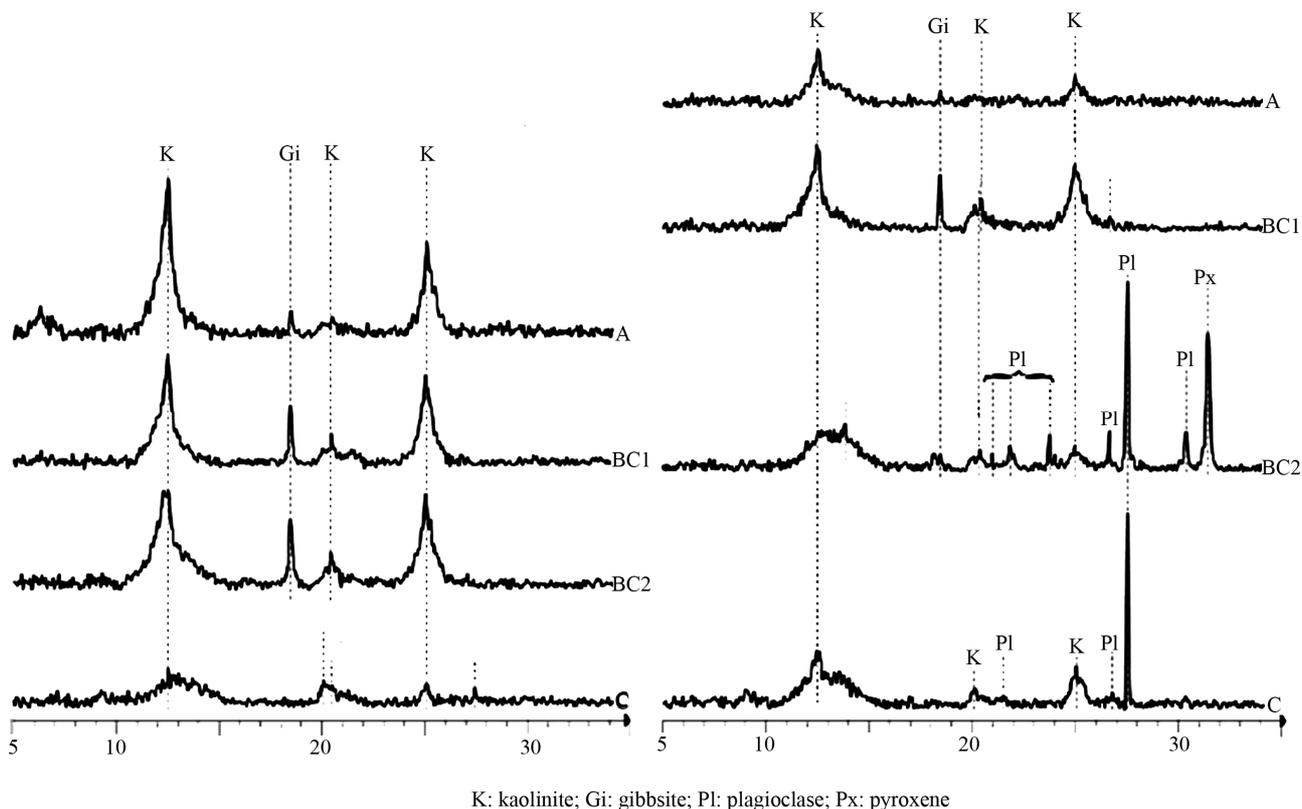K: kaolinite; Gi: gibbsite; Pl: plagioclase; Px: pyroxene

Figure 3. X-ray patterns of the studied soil pedons.

is the remaining primary mineral in weathered saprolite (C horizon) and represents 14% of the minerals (**Table 4**). Plagioclase and pyroxene are present in pedon TO. Plagioclase displays a sharp and intense peak at 0.323 nm in the weathered rock fragments (**Figure 3**). In the weathered rock fragments, it represents 57% to 64% of the minerals. Peak representing pyroxene is at 0.283 nm and the weathered saprolite has 23% of this mineral.

The short-range ordered minerals and the organometal complexes: The organometal complexes correspond to the Al (and/or Fe)-humus complexes extracted by sodium pyrophosphate (**Table 3**). These complexes are found in small quantities at soil surface (**Table 4**).

The short-range ordered minerals identified correspond to allophane and ferrihydrite. Allophane contents are relatively low in both soils (less than 1.2%) and varied little with depth. Ferrihydrite contents are slightly higher throughout these soils (2.3% to 2.9% in pedon ZA and 1.1 to 2.9% in pedon TO) (**Table 4**).

The long-range ordered minerals: The long-range ordered minerals identified by XRD (**Figure 3**) are kaolinite and gibbsite, and goethite was quantified by selective extraction (**Table 4**). Kaolinite has peaks at about 0.715 nm and 0.357 nm. It is the most abundant secondary mineral in these soils representing 54% to 71% and 3% to

75% of the minerals in pedons ZA and TO, respectively (**Table 4**). The largest amount of kaolinite is in the topsoil. Gibbsite is also prominent in these soils, with major peak around 0.485 nm. It is the second most abundant secondary mineral in these soils and varies from 12% to 29% and 3 to 19% in pedons ZA and TO, respectively. This mineral is present in largest amounts in the BC horizons, and decreases in concentration in the A and C horizons (**Table 4**). Goethite is the only iron bearing mineral in these pedons and has a relatively uniform concentration with depth in both pedons. It varies from 10% to 12% and 6% to 11% in pedons ZA and TO, respectively (**Table 4**).

3.4. Soil Geochemistry

Silica contents (**Table 5**) decrease from about 43% in the fresh rock to 28% in the soil surface. Alkalis (K_2O and Na_2O) and alkaline earth (CaO and MgO) elements also decrease in soil relative to the fresh rock (**Table 5**), and remain very low throughout the profiles. Inversely, Al_2O_3 and Fe_2O_3 contents increase in soil (23% Al_2O_3; 21% of) relative to the fresh rock (about 12% Al_2O_3 and 13% Fe_2O_3). The Al_2O_3 contents decrease very slightly at soil surface (about 20%) while Fe_2O_3 did not vary much throughout the profiles.

The molar ratio Ki (SiO_2/Al_2O_3), an indicator of the

Table 5. Major elements abundances and weathering indexes in the selected pedons.

Studied pedons	Soil horizon	samples	Major elements abundance (%)										Ki	TRB (mg·kg⁻¹)	CIA (%)	IMob (%)
			SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	MnO	P_2O_5				
ZA pedon	A (0 - 52 cm)	A	28.1	20.8	19.5	4.0	0.2	0.7	0.4	0.2	0.3	0.4	1.4	57.6	65.4	17.2
	BC (52 - 160 cm)	BC1	25.4	22.8	19.5	3.9	0.1	0.6	0.3	0.2	0.2	0.4	1.1	52.4	67.6	21.4
		BC2	26.2	22.7	19.7	3.9	0.1	0.7	0.3	0.2	0.2	0.4	1.2	46.1	67.6	24.5
	C (160 - 260 cm)	C	29.0	19.7	21.9	4.5	0.2	3.8	0.3	0.2	0.3	0.6	1.5	48.9	64.3	20.7
	R (260 cm -)	R	43.3	12.6	13.3	2.8	10.5	12.5	0.9	3.0	0.2	0.7	3.4	252.9	46.6	-
TO pedon	A (0 - 44 cm)	A	27.6	20.0	19.3	3.6	0.2	0.9	0.4	0.2	0.3	0.4	1.4	62.6	63.8	19.4
	BC (44 - 206 cm)	BC1	30.9	22.4	18.8	3.6	0.1	0.7	0.4	0.2	0.3	0.4	1.4	57.1	66.3	20.0
		BC2	39.6	21.9	13.9	2.6	0.2	0.7	1.1	0.6	0.3	0.3	1.8	66.7	63.6	6.9
	C (206 - 360 cm)	C	32.9	20.3	19.4	4.0	0.2	14.0	0.6	0.2	0.3	0.4	1.6	101.0	63.7	14.5
	R (360 cm -)	R	42.2	12.1	13.9	2.9	10.9	12.7	1.2	2.7	0.2	0.8	3.5	170.7	45.0	-

Ki, SiO_2/Al_2O_3; TRB, total reserve in bases; CIA, chemical index of alteration; IMob, mobility index.

relative mobility of Si to Al (**Table 5**), decreases in relation to the parent material (from 3.5 to 1.1). The total reserve in base (TRB), a measure gives of the weathered primary minerals in soils, also drops from the fresh rock (252.9 and 170.7 mg·kg⁻¹ in pedons ZA and TO, respectively) to the weathered level (46.1 and 66.7 mg·kg⁻¹, respectively), suggesting the depletion of weatherable minerals in the topsoil. Inversely, the chemical index of alteration (*CIA*), representing the weathering intensity, and the mobility index (*IMob*) used to evaluate the intensity of CaO, Na_2O and K_2O exportation during weathering [24], increase drastically from the fresh rock (46.6 and 45.0% of *CIA*, in pedons ZA and TO, respectively) to the topsoil, with their highest values in horizon BC (67% *CIA*, 24.5% *IMob*). This is consistent with a moderately weathering intensity in a highly leaching milieu.

Enrichment-depletion of chemical elements in the studied soils was assessed using enrichment factors (EF). The chemical elements analysed are grouped into enriched (EF > 1.00) and depleted (EF < 1.00) elements according to their enrichment factors (**Figure 4**). Enriched elements are Al_2O_3 and Fe_2O_3. Al_2O_3 is enriched in both studied pedons, with EF varying from 1.16 to 1.30 in pedon ZA and 1.22 to 2.02 in pedon TO. The highest EFs for Al_2O_3 are in the subsurface horizon BC. Fe_2O_3 is slightly enriched in the studied profiles, with EF not exceeding 1.03 in pedon ZA and 1.12 in pedon TO. Depleted elements are SiO_2, CaO, MgO, K_2O and Na_2O. SiO_2 is moderately depleted, with EF varied from 0.42 to 0.45 in pedon ZA, and 0.53 to 1.05 in pedon TO. K_2O also is moderately depleted in the studied profiles (EF from 0.21 to 0.31 in pedons ZA and 0.27 to 1.02 in pedon TO). But, CaO, MgO and Na_2O are strongly depleted in the studied profiles, with EF < 0.2.
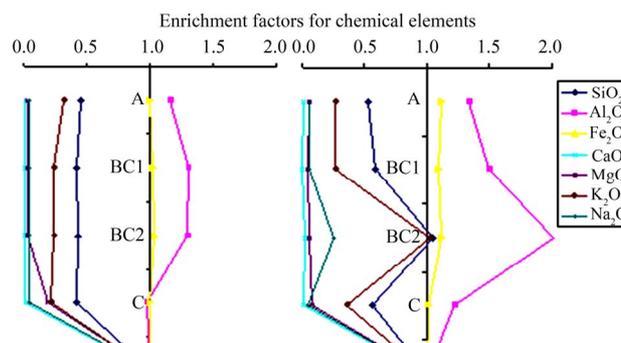

Figure 4. Graphs of chemical element mobility in the studied soil pedons.

4. Discussion

The studied soils belong to the reference group of Andosol in the WRB system [4] as indicated by the low bulk density (<0.7 g·cm⁻³), Alo + 0.5Feo about 2% and the P retention ≫90% in their surface horizon A. The high organic carbon in the surface horizon A (OC: 5.9% and 7.0%) confirms that the pedogenetic conditions in andic soils favour accumulation of organic matter [25]. They are depleted of bases with the base saturation <15% (not shown) which results in the use of the *dystric* qualifier as suffix for this WRB reference group [4]. The low content of Si extracted by ammonium oxalate (Sio: 0.15%) (**Table 3**) and the Alp/Alo ratio > 0.5 (0.7 in pedon ZA and 0.6 in pedon TO) (not shown) which indicate that Al is predominantly organically bound [26] suggest that these soils owe their andic properties to Al-humus complexes and therefore belong to the non-allophanic category of andosols. These remarks justify the use of the *aluandic* qualifier as prefix for this reference group. Therefore, these

soils key out as *aluandic ANDOSOLS* (*dystric*) according to the WRB soil classification system [4].

Referring to the weathering process, kaolinite and goethite are the dominant weathering products in both soil pedons. Their presence in the weathered saprolite is accompanied by the decrease of *TRB*, the increase of *IMob* and the EFs far below 0.6 for Si, Ca, Mg, K and Na. These observations point out an important depletion of silica and total leaching of base cations, highlighting a sparingly hydrolyses [19] in subsoil. Thus, in these soils, weathering leads to faster release of Al, Fe and Si which are initially incorporated into allophanic and ferrihydrite minerals. These short-range ordered minerals are transient and undergo crystallization into poorly crystallized kaolinite and goethite under humid conditions [17,27]. In the topsoil, kaolinite, goethite, gibbsite and organometal complexes are present. Occurrence of gibbsite isolated in the topsoil has been reported in various andosols worldwide [6,28-31]. It was largely attributed to localised desilication of kaolinitic minerals during intense leaching in highly acid milieu under perudic conditions. Also, the topsoil is strong acidic (pH < 4.7), enhancing the formation of organometal complexes [32] and accumulation of organic matter which limit precipitation of Al and Si [33], and result in anti-allophanic effect [9]. In fact, below pH 4.9, Al is in a monomeric or organically complexed form and is not available for incorporation into mineral structure [9]. About the weathering intensity, the *CIA* between 60 and 70% and the abundance of secondary minerals indicate that the weathering gradient of these soils is moderately high [34]. This is emphasized by the absence of weatherable primary minerals at soil surface (low *TRB*), which attests that the fresh rock has been completely weathered.

From findings, a major difference in the andosolization process operating on old trachytic formations from those operating on recent strombolian deposits is the formation of kaolinite instead of halloysite in the late quaternary strombolian cone soils. This may be consistent with the less humid conditions prevailing in the NE slope of Mount Bambouto, highly influenced by relatively dry wind from Sahara desert named Harmattan [35]. Except the above difference, both Andosols in Mount Bambouto show similar morphology (shallow weathered A-BC-C soil pedons) and approximately the same mineral composition (organometal complexes, Al bearing 1:1 clay minerals, gibbsite and goethite). Consequently, the similar weathering processes are likely operating in both sites at Mount Bambouto, and therefore, the discontinuities of the volcanic activities (rocks age) of these sites have little influence.

5. Conclusions

In the late quaternary strombolian deposits from Mount Bambouto, andic soils refer to *aluandic ANDOSOLS* (*dystric*). They derive from the andosolization process which corresponds to fast and intense release of Si, Al and Fe during rapid hydrolysis of volcanic products under humid conditions. Transient allophanic and ferrihydrite minerals are formed that crystallized into kaolinite, gibbsite and goethite. Part of released Al (and Fe) is bounded at topsoil by organic acids to form stable and less mobile organometal complexes. Thus in Mount Bambouto, andosols are non-allophanic which seem to have developed at the same period despite the wide range of rock ages and type.

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