


Study of the Geochemistry, Mineralogy and Morphological Organization of Soils in the Northwest Region of Ngaoundere, Adamawa Cameroon: Identification and Characterization of a Paleosol

Dalil Adoulko^{1*}, André Sini², Isaac Daama³, Abdoul Aboubakar^{4,5}, Simon Djakba Basga⁶, Béral Djetenbé⁷, Bahouro Arka⁸, Bello Hamagourdo⁷, Rigobert Tchameni⁷, Jean Pierre Nguetnkam⁷

¹Department of Earth Sciences and Environment, Faculty of Science, University of Garoua, Garoua, Cameroon

²Department of Mining Engineering, School of Geology and Mining Engineering, University of Ngaoundere, Ngaoundere, Cameroon

³Department of Oil and Gas Engineering, School of Geology and Mining Engineering, University of Ngaoundere, Ngaoundere, Cameroon

⁴Center for Geological and Mining Research (CRGM), Garoua, Cameroon

⁵Department of Earth Sciences, Faculty of Science, University of Dschang, Dschang, Cameroon

⁶Institute of Agricultural Research for Development (IRAD), Garoua, Cameroon

⁷Department of Earth Sciences, Faculty of Science, University of Ngaoundere, Ngaoundere, Cameroon

⁸Chadian Institute of Agronomic Research for the Development (ITRAD), Route de Fourcha Djamena, Chad

Email: adoulko.dalil@gmail.com

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Abstract

The study of a pedological sequence in Darang allowed to characterize the soil in the Northwest of Ngaoundere. After a description of the landscape, a toposequence of approximately 1050 meters long was the subject of this work. For this purpose, three pedological pits were opened following the toposequence in order to discover the internal organization of the soil and to allow their characterizations. 18 soil samples were collected from the center of each horizon, described and analyzed at the morpho-structural, physico-chemical, mineralogical and geochemical levels. The physico-chemical analyses were conducted according to standard methods; the mineralogy is determined by X-ray diffraction (XRD) and geochemistry analysis by ICP-AES. The results of analyses reveals that the soils of Darang are made up of two distinct organizational levels: 1) On the surface, the moderately differentiated soils formed on basaltic materials occupy the upper part of the profiles; they are brown (7.5YR 3/4), very clayey and with

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a lumpy to polyhedral structure; 2) In depth, the paleosols, thicker, well-differentiated soils, formed on ancient granitic materials, which occupy the lower part of the profiles; they are dark brown (7.5YR 4/6), clayey and with a polyhedral structure. Generally, these soils have an acidic to neutral pH, with low exchangeable base contents, a low saturation rate (20.01%) and a low Cation Exchange Capacity (51.04 meq/100g). The most dominant oxides are: 35% of SiO₂, 20% of Al₂O₃) and 15% of Fe₂O₃). The assessment of the degree of alteration shows that the alteration is intense and discontinuous along the soil profiles. Quartz, feldspar, kaolinite, gibbsite, goethite and hematite constitute the mineralogical assemblage.

Keywords

Darang Soils Characterization, Paleosols, Toposequential Organization, Clay Minerals, Adamawa-Cameroon

1. Introduction

This article aims to contribute to the understanding of soils in the northwest for the sustainable management of resources. The analysis of morphological, mineralogical, and geochemical data is fundamental to reconstructing the environment, understanding the past, and ultimately informing actions in the present and planning for the future. Soil studies northwest of Ngaoundere have revealed paleosols buried beneath basaltic rocks. Paleosols are ancient soils buried under sedimentary or volcanic formations, several natural archives that allow us to reconstruct the history of the past (Retallack, 2005; Targulian & Krasilnikov, 2007; Nguetnkam et al., 2020). Their study, based on morphological observation, mineralogical and geochemical analyses, helps to understand how landscapes have evolved over time (Bachelier & Laplante, 1953; Fedoroff et al., 2010; Tsozué et al., 2012; Nguetnkam et al., 2020). Adamawa region in Cameroon is marked by a complex geological history, with volcanic eruptions and strong weathering under a humid tropical climate (Sieffermann, 1969; Njonfang et al., 2008). Paleosols are valuable witnesses of the evolution of terrestrial ecosystems, influenced by biological and abiotic factors (Braun et al., 2005; Tchindjang et al., 2016). In Ngaoundere, the discovery of a paleosol buried under Quaternary deposits raises important questions about its formation and its role in the local dynamics of landscapes. This work aims to analyze the structure, the mineralogical and chemical composition of paleosols to understand the processes that led to the formation.

1.1. Location of Study Area

The study area is located in the Adamawa region, in the north west from Ngaoundere between 7°22' and 7°23' North latitude and 13°29' and 13°32' East longitude (Figure 1).

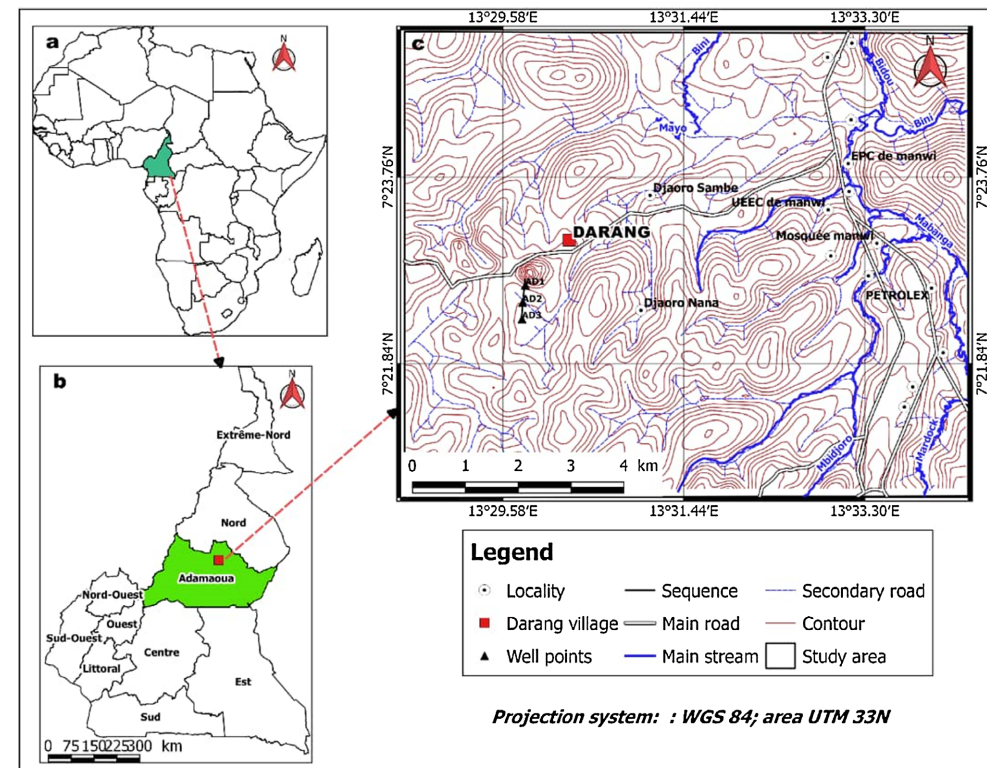


Figure 1. Localization of study area, (a) Map of Africa indicating Cameroon, (b) Map of Cameroon showing the Adamawa region indicating the study area, (c) The study area.

1.2. Geological Context

The region experienced significant volcanic activity during the Mio-pliocene, with alkaline basalts and differentiated rocks such as trachyte and phonolite (Gouhier et al., 1974; Oustriere, 1984). These volcanoes, scattered around Ngaoundere, left lava flows, cinder cones, and pyroclastic deposits. The region is part of the Cameroon Volcanic Line, a large geological structure marked by magmatic episodes since the Cenozoic period (Temdjim et al., 2004). All the lavas belong to a sodic alkaline series (Temdjim, 2010). In the Miocene, volcanic episodes emitted lavas at different locations on the Adamawa plateau and the final volcanic episode is represented by about sixty eruptive centers scattered within a radius of 25 kilometers around the town of Ngaoundere (Temdjim, 2010): pyroclastic deposits of phreatomagmatic origin consisting mainly of aerial fallout; numerous scoria cones and interstratified basaltic flows. A mugearite flow from the Wakwa region was dated to 0.91 ± 0.06 Ma by the K-Ar method (Temdjim, 2010). The volcanic formations around Ngaoundere have been grouped into three series of emissions (Temdjim et al., 2004) and in accordance with the observations of Gèze (1943) in western Cameroon: 1) Alkaline basalts from Plio-Quaternary volcanic eruptions; 2) Metamorphic rocks (gneisses, migmatites) of the Precambrian basement; 3) Holocene alluvial-colluvial deposits, partially covering the paleosols. The Ngaoundere sector is part of the Cameroon Volcanic Line, a major structure in Central Africa marked by episodes of Cenozoic magmatism (Fitton & Upton, 1987;

Tematio, 1994).

1.3. Climatic and Pedoclimatic Context

Located between 1000 and 1500 m, the Adamawa highlands have a subtropical climate with a so-called tropical transitional rainfall regime, with a rainy season from May to October with average annual rainfall of 1500 mm and a marked dry season from November to April (Atougour et al., 2019). Rainfall is 1.58 m, the average temperature is 22°C with absolute extremes of 9.5°C and 35°C; the average relative humidity, around midday, varies from 35% at the beginning of the year to 85% in July (Bachelier & Laplante, 1953; Atougour et al., 2019). These conditions favor strong chemical alteration of the rocks, but also increased vulnerability to erosion, particularly in a transition zone between savannah and semi-deciduous forest (Yemefack et al., 2005).

2. Materials and Methods

2.1. Field Work

The field work began with a geological and geomorphological survey. This step relied on topographic and geological maps to delimit the study area and identify key elements to understand the formation of local soils. A toposequence was then used to determine the location of the wells. A total of three sites were selected to dig pedological pits. The morphological description of these pits was carried out according to the precision of pedological criteria, including color, structure, thickness, texture, biological activity, the presence of rock fragments and the transition with the underlying horizon. This study was conducted on a toposequence with a length of 1050 meters and an altitude varying between 1120 and 1103 meters from the top to the base. The depth of the profiles varies from 830 cm to 110 cm from the top to the base of the toposequence.

2.2. Laboratory Analyses

The analyses carried out in the laboratory included physicochemical, geochemical and mineralogical analyses.

2.2.1. Physicochemical Analyses

These analyses were carried out at the Soil Analysis and Environmental Chemistry Laboratory of the Faculty of Agronomy and Agricultural Sciences (FASA) of the University of Dschang. The objective was to understand the variation of elements along a toposequence. The parameters studied included pH, organic carbon (CO), total nitrogen (TN), exchangeable cations, cation exchange capacity (CEC) and particle size.

2.2.2. Geochemical and Mineralogical Analyses

Geochemical analyses were carried out at the ALS GEOCHEMISTRY Laboratory in Ontario, Canada. They focused on major and trace elements in order to determine the origin, evolution and distribution of the elements and thus to identify

the chemical composition of the soils. For these analyses, a sample was first fused with lithium metaborate, then dissolved in acetic acid. The resulting solution was analyzed directly. The major elements were determined by ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectroscopy). Quality control was ensured using international geostandards. The major elements were expressed as a percentage of oxide, based on the weight of the sample previously dried at 110°C. The relative uncertainty of this analysis is approximately 1%, distributed proportionally over the content of each oxide. The analyses focused on the determination of major element oxides (SiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, Na₂O, K₂O, TiO₂, P₂O₅, MnO and Cr₂O₃).

Mineralogical analysis of the total fraction was performed by X-ray diffractometry (XRD) at GeoLabs Geosciences Laboratories in Ontario, Canada. The objective was to identify and quantify soil's minerals to understand their physical and chemical properties.

From these geochemical data, the chemical alteration index (CIA) was determined to quantify the alteration of the studied soils. It is calculated by applying the following formula:

$$CIA = \frac{Al_2O_3}{Al_2O_3 + CaO + Na_2O + K_2O} \times 100 \quad (1)$$

The chemical alteration index is used to calculate the degree of transformation of primary minerals into secondary minerals (Nesbitt & Young, 1982; Nesbitt & Wilson, 1992; Price & Velbel, 2003).

$$MIA = 2(CIA - 50) \quad (2)$$

Voicu and Bardoux (2002) established that for MIA < 20% the alteration is insignificant; MIA between 20% - 40%, the alteration is weak; between 40% - 60%, the alteration is moderate and >60% the alteration is intense. Values of 100% correspond to total alteration.

The SiO₂/Al₂O₃ ratio of (Ruxton, 1968) allows to evaluate the leaching of silica in relation to alumina. It is an indicator of the type of clay present in the alteration products.

The Al₂O₃/Fe₂O₃ ratio of (Jenny, 1941) allows to compare the mobility of aluminum and iron during alteration. When it is greater than 1, it generally indicates an aluminous medium in which minerals such as kaolinite, gibbsite, boehmite and diaspore develop. While its low values are symptomatic of a ferruginous environment where iron oxides and oxyhydroxides crystallize.

The SiO₂/TiO₂ ratio, according to Goldich (1938), Potter & Pettijohn (1963), and Nesbitt & Young (1982), is a fundamental geochemical indicator in pedology for assessing the intensity of chemical weathering and soil maturity.

3. Results

3.1. Morphological Organization of the Studied Soils

Along the toposequence (Figure 2), three soil pits were manually opened and

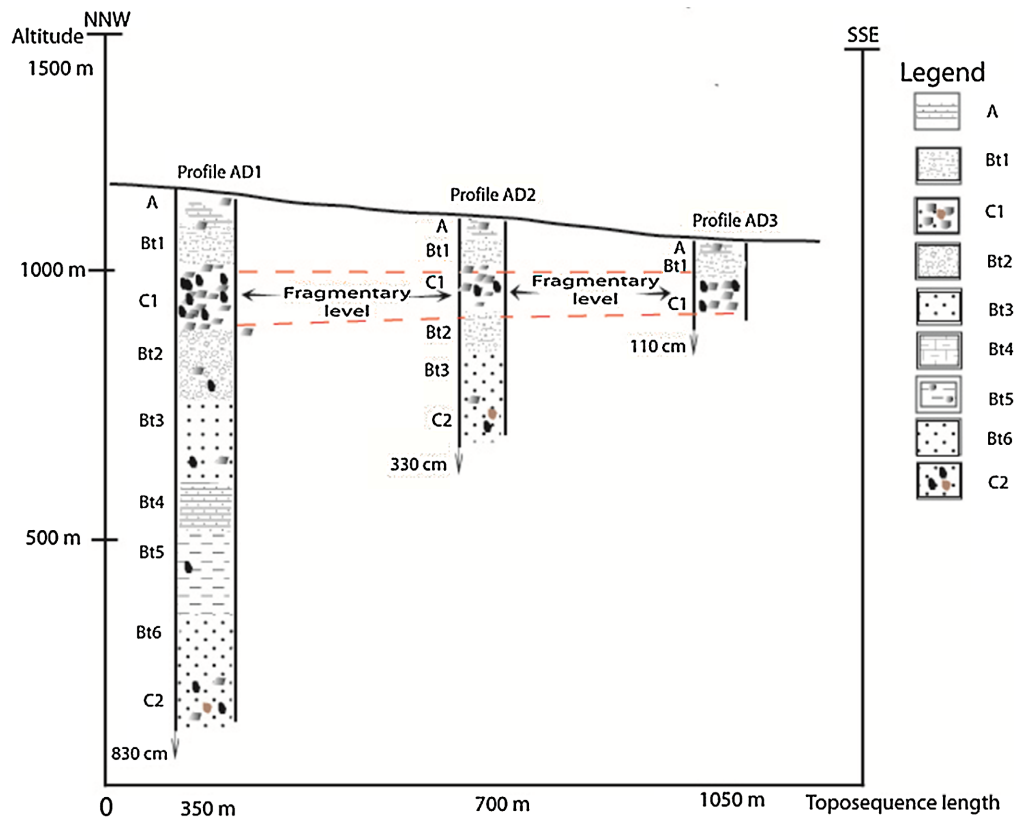


Figure 2. Morphological sketch of the toposequence showing the three pedological profiles as a function of depth.

described according to the soil description criteria, including color, structure, thickness, texture, biological activity, the presence of rock fragments and the transition with the underlying horizon. Depending on the topographic position, a soil pit was opened at the top of the slope, at mid-slope and at the bottom of the slope. Generally, the surface horizons are brown for all surface horizons and red to yellowish red for the deep horizons. The texture is clayey to very clayey with polyhedral to fragmentary structures. The upper horizons are formed on less altered basalts while the lower horizons are formed on more altered granites. These profiles are thick and well differentiated. At the top, profile AD1 (**Figure 3**) was produced at the top of the slope at coordinates $07^{\circ}22.633'$ North latitude, $13^{\circ}29.812'$ East longitude and an altitude of 1120 m. This profile has a thickness of 830 cm, consists of nine (09) horizons and presents the following successions from top to bottom (**Table 1**). Profile AD2 (**Figure 4**) is carried out mid-slope, in a field that has been fallow for several years at coordinates $07^{\circ}22.507'$ North latitude, $13^{\circ}29.801'$ East longitude and altitude 1109 m. This profile measures 330 cm in depth, made up of six (06) horizons which are presented as follows (**Table 2**). Profile AD3 (**Figure 5**) is carried out at the bottom of the slope, in an uncultivated area at coordinates $07^{\circ}22.343'$ North latitude, $13^{\circ}29.860'$ East longitude and altitude 1103 m. This profile has a thickness of 110 cm and consists of three (03) horizons and presents from top to bottom the following successions (**Table 3**).

Table 1. Macromorphological description of profile AD1 at the top of the slope.

Sample	Horizons	Depth (cm)	Dry Colour	General characteristics
P11	A	0 - 17	Brown (7.5YR 4/4)	Polyhedral, silty-clayey and not very compact, presence of nodules and fragments of altered basalts.
P12	Bt ₁	17 - 87	Blackish brown (5YR 3/3)	Polyhedral, clayey, not very compact, presence of numerous fragments of basalt and some fragments of altered granite.
P13	C ₁	87 - 157	Blackish brown (7.5YR 3/4)	Fragmentary, clayey texture, presence of fragments of unaltered and/or slightly altered basalt and some blocks of granite.
P14	Bt ₂	157 - 267	Blackish brown (7.5YR 3/4)	Polyhedral, clayey texture, compact, presence of fragments of basalts, altered granites and some rare yellow spots.
P15	Bt ₃	267 - 392	Blackish brown (7.5YR 3/4)	Polyhedral, clayey texture, compact, presence of fragments of basalts and some rare fragments of altered granites.
P16	Bt ₄	392 - 447	Dark brown (7.5YR 4/6)	Polyhedral, clayey texture, compact, presence of altered basalt fragments.
P17	Bt ₅	447 - 577	Reddish yellow (7.5YR 6/6)	Fragmentary, clayey texture, compact, presence of fragments of altered basalts and granites.
P18	Bt ₆	577 - 667	Reddish yellow (7.5YR 7/6)	Fragmentary, clayey texture, compact, presence of fragments of altered basalts.
P19	C ₂	667 - 830	Dark brown (7.5YR 5/6)	Fragmentary, clayey texture, very compact, presence of fragments of altered basalts and granites.

Table 2. Macromorphological description of the AD2 profile at the mid-slope.

Sample	Horizons	Depth (cm)	Dry Colour	General characteristics
P21	A	0 - 14	Blackish brown (7.5YR 3/4)	Lumpy, clayey texture, not very compact, presence of basalt fragments.
P22	Bt ₁	14 - 34	Blackish brown (7.5YR 3/4)	Polyhedral, clayey texture, not very compact, presence of altered basalt fragments.
P23	C ₁	34 - 114	Blackish brown (7.5YR 3/3)	Polyhedral with numerous fragments of altered basalt and a few rare fragments of granite, clayey texture and compact.
P24	Bt ₂	114 - 184	Brown (7.5YR 3/4)	Polyhedral, clayey texture, compact, presence of large fragments of basalt and a few rare fragments of granite.
P25	Bt ₃	184 - 274	Dark brown (7.5YR 4/6)	Polyhedral, clayey texture, compact, presence of fragments of basalts in the process of alteration and a few rare fragments of altered granites.
P26	C ₂	274 - 330	Brown (7.5YR 5/4)	Polyhedral, clayey texture, not very compact, presence of fragments of altered basalts and granites.

Table 3. Macromorphological description of profile AD3 at the bottom of the slope.

Sample	Horizons	Depth (cm)	Dry Colour	General characteristics
P31	A	0 - 22	Very blackish gray (7.5YR 3/1)	Lumpy, silty-clayey texture, not very compact, presence of very rare nodules.
P32	Bt ₁	22 - 46	Blackish gray (7.5YR 4/1)	Polyhedral, very clayey texture, compact, some rare yellow spots, presence of desiccation cracks.

Continued

P33	CI	46 - 110	Gray (7.5YR 5/1)	Polyhedral, very clayey texture, very compact, presence of an abundance of yellow spots, presence of altered basalt fragments, presence of desiccation cracks, presence of very hard nodules.
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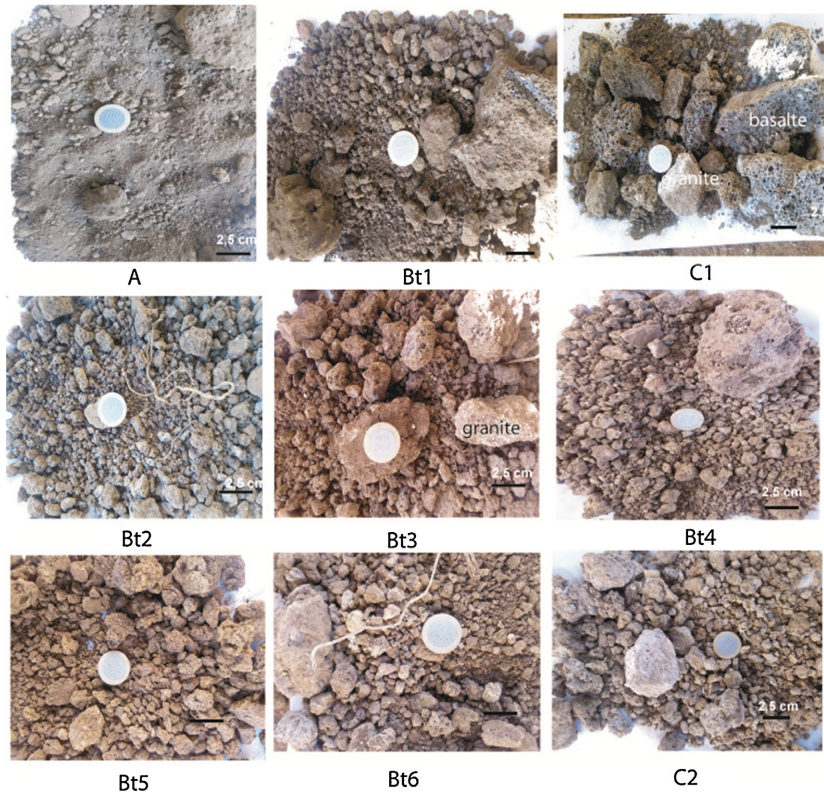


Figure 3. Morphological organization of the horizons of the AD1 profile at the top of the slope.

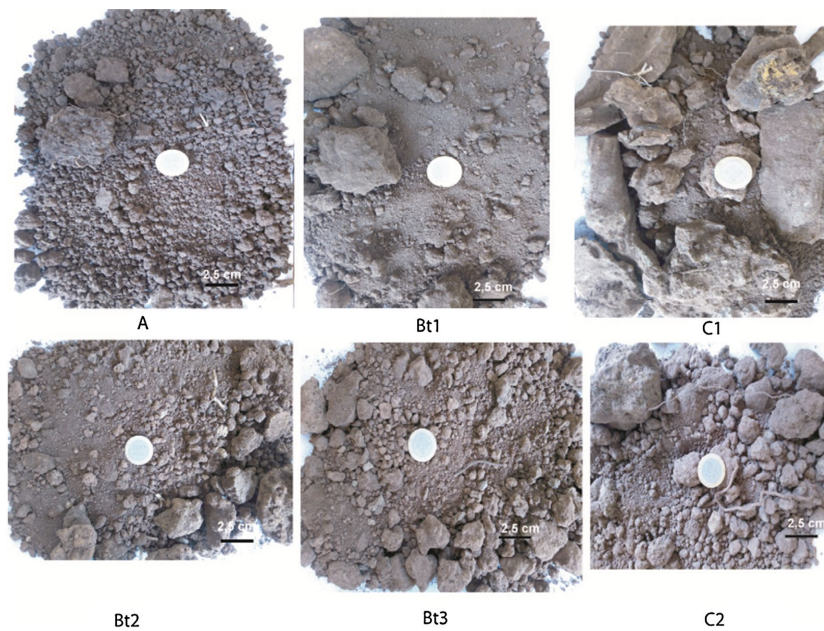


Figure 4. Morphological organization of the horizons of the AD2 profile at mid-slope.

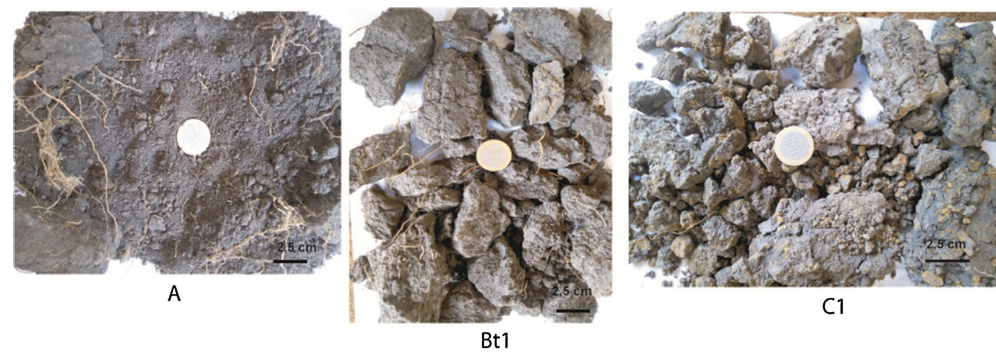


Figure 5. Morphological organization of the horizons of the AD3 profile at the bottom of the slope.

3.2. Physicochemical Characteristics of the Studied Soils

The physicochemical analyses are presented in **Table 4**. They aim to determine the texture, pH, organic components (CO), exchangeable cations, cation exchange capacity (CEC), saturation rate and granulometry of the soils.

Table 4. Data on the physicochemical characteristics of the studied soils.

Hori- zon	Depth (Cm)	pH in water 2.5:1	CO	Mo (%)	N	N (g/kg)	C/N	Ca	Mg (meq/100g)	K	Na	P (mg/kg)	SBE (meq/100g)	CEC	S/T (%)	
P11	A	0 - 17	5.2	4.57	7.88	0.22	2.18	21	8.08	3.84	0.34	0.80	34.14	13.06	65.28	20.01
P12	Bt1	17 - 87	5.3	2.21	3.81	0.13	1.34	17	10.32	6.96	0.90	1.32	16.28	19.49	72.48	26.90
P13	C1	87 - 157	6.1	0.84	1.44	0.06	0.61	14	10.24	5.76	2.52	1.49	17.80	20.01	59.20	33.80
P14	Bt2	157 - 267	6.6	0.53	0.92	0.03	0.32	17	18.32	8.08	1.49	1.32	12.86	29.21	76.00	38.43
P15	Bt3	267 - 392	7.0	1.30	2.23	0.04	0.41	30	15.20	10.72	0.58	1.14	14.77	27.65	66.72	41.44
P16	Bt4	392 - 447	7.0	1.22	2.10	0.03	0.28	44	11.76	12.32	0.16	0.80	24.12	25.04	90.88	27.56
P17	Bt5	447 - 577	6.7	1.52	2.63	0.03	0.29	53	24.96	13.12	0.34	1.14	26.89	39.56	92.16	42.93
P18	Bt6	577 - 667	6.8	0.99	1.71	0.03	0.29	34	5.36	21.76	0.24	0.63	59.43	27.99	69.76	40.13
P19	C2	667 - 830	7.1	0.46	0.79	0.01	0.11	44	10.24	15.36	0.10	0.46	14.44	26.16	66.08	39.58
P21	A	0 - 14	5.6	4.95	8.54	0.22	2.23	22	7.12	7.76	0.16	0.46	55.08	15.50	62.08	24.97
P22	Bt1	14 - 34	5.2	1.52	2.63	0.17	1.69	9	6.56	4.48	0.16	0.46	28.60	11.66	54.88	21.24
P23	C1	34 - 114	5.3	4.57	7.88	0.13	1.26	36	8.16	0.08	0.16	0.28	21.36	8.69	51.04	17.02
P24	Bt2	114 - 184	5.9	2.29	3.94	0.05	0.50	46	10.88	5.84	0.45	0.28	16.88	17.46	52.96	32.97
P25	Bt3	184 - 274	6.1	1.37	2.74	0.04	0.35	39	16.24	10.64	0.58	0.28	37.49	27.75	58.24	47.65
P26	Bt4	274 - 330	6.3	0.53	0.92	0.02	0.18	30	16.80	9.76	0.73	0.97	8.18	28.27	55.04	51.35
P31	A	0 - 22	5.0	6.48	11.16	0.13	1.30	50	12.72	15.12	0.90	0.80	14.84	29.54	78.08	37.84
P32	Bt1	22 - 46	5.5	3.05	5.25	0.11	1.13	27	24.96	17.12	1.08	0.80	38.68	43.96	84.80	51.83
P33	C1	46 - 110	6.0	1.52	2.63	0.18	1.83	8	17.12	13.76	0.60	0.63	11.21	32.11	56.00	57.33

increases with depth, from the surface to the depth, we move from sandy texture to very clayey texture. The textural parameters of the sequence profiles placed in the Jamagne textural diagram show that the soils of Darang have varying textures along a sequence: very clayey (ALO), clayey (AL, A), sandy loam (LSA) and sandy (SA). In general, the soils have a very clayey texture.

3.2.2. Variation of pH and Organic Constituents

The pH of the soils studied is strongly to weakly acidic (5.2 - 5.3) for the surface horizons and weakly acidic to neutral (6.1 - 7.1) for the deep horizons. For the profiles located at the top and mid-slope, it is strongly acidic to weakly acidic (5.2 - 5.6) for the lower slope profile (Figure 7(a)). In general, the pH increases with depth (Figure 7(a)). However, for the mid-slope profile, there is first a decrease in pH up to a depth of 2 m before its increase with depth. The contents of organic components are very low: N (0.01% - 1.22%), CO (0.52% - 6.48%), OM (0.79% - 11.16%) and C/N (0.8% - 53%). From surface to depth, the content of OM, N and CO decreases in all profiles. C/N is less than 25% in the horizons of surface of the upper and mid-slope profiles. While, in the profile located at the bottom of the slope, it is lower and decreases with depth. (Figure 7(b)) shows the variation of organic components as a function of depth. The contents of N, CO and Organic matter vary little along the profile regardless of the topographic position (Figure 7(b)).

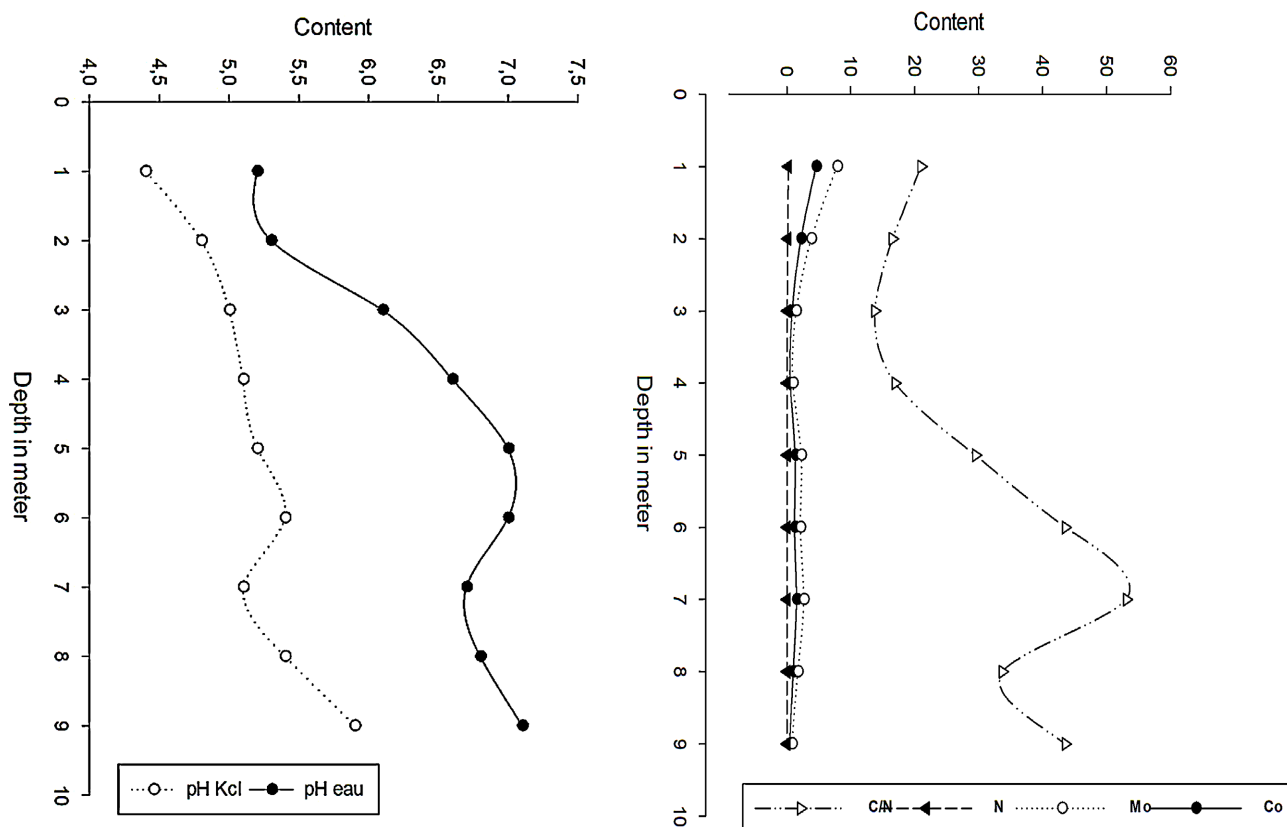
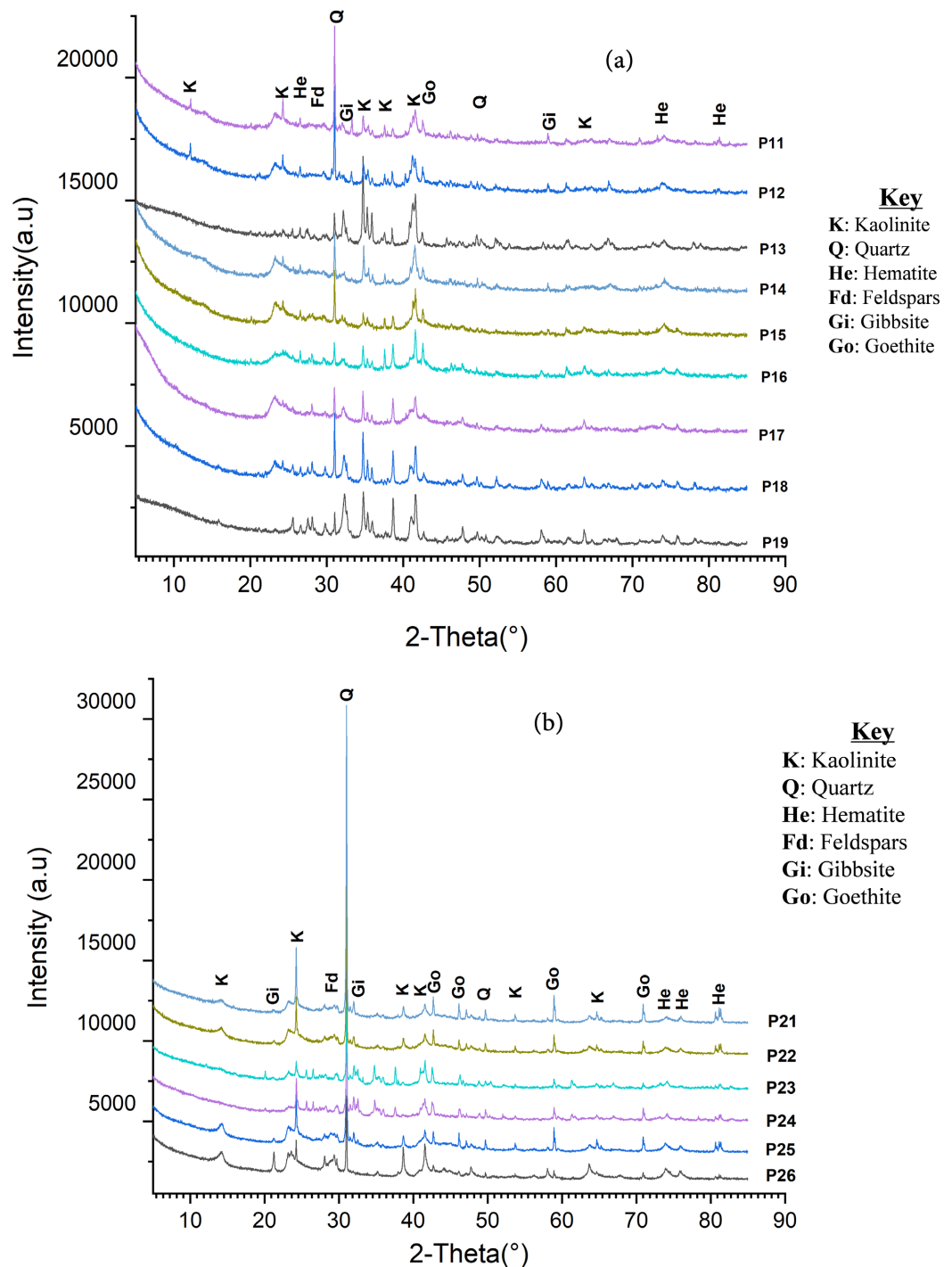


Figure 7. Variation of pH (a) and organic compounds (b) as a function of depth.

3.3. Mineralogical Characterization of the Studied Soils

The XRD diagrams of the normal oriented blades of the different samples allow to identify of the following minerals: quartz, feldspars, goethite, kaolinite, gibbsite and hematite. These minerals are determined by observing their characteristic peaks and possibly their harmonics (**Figure 8**). Kaolinite, goethite, and hematite are the most abundant minerals present in all profiles. These minerals are more abundant towards the base of the profile. While the surface of the profiles is



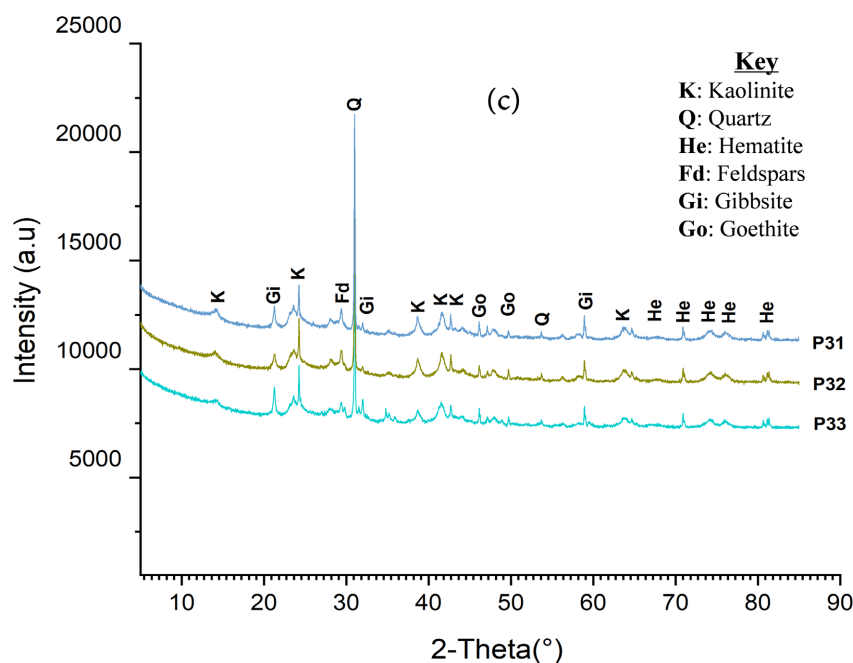


Figure 8. XRD diagram of the studied soils: (a) AD1; (b) AD2, (c) AD3 profile sample.

dominated by minerals such as feldspars and quartz. XRD patterns highlight the distribution of different minerals in the soil profiles (**Figures 8(a)-(c)**). The crystallochemical phenomena that prevailed during weathering processes are monosiallization and allitization.

3.4. Geochemical Characterization of the Studied Soils

Major Elements

The Darang soils have high silica and aluminum contents compared to other major elements (**Table 5**). SiO_2 concentrations are between 24% and 48.4% and rich in Al_2O_3 with concentrations between 14.15% and 45%. Fe_2O_3 concentrations are average between 14.6% and 29.7% and TiO_2 between 2.58% and 6.11%. The contents of CaO, MgO, K_2O , P_2O_5 , Na_2O , Cr_2O_3 and MnO are low. Loss on ignition is between 4.82 and 18.4.

Table 5. Distributions of major elements (in %) in soil horizons, LOI: Loss on Ignition.

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Cr_2O_3	TiO_2	MnO	P_2O_5	SrO	BaO	LOI	Total	SI/Al	Al/Fe	CIA	MIA
P11	35.2	18.2	15.15	1.88	3.85	0.26	0.54	0.04	3.31	0.31	0.83	0.01	0.08	18.4	98.07	1.93	1.20	87.16	74.33
P12	35.1	21	16.65	2.09	4.17	0.29	0.5	0.04	3.68	0.31	0.57	0.02	0.1	16.3	100.83	1.67	1.26	87.94	75.88
P13	38.9	18.6	15.15	5.85	6.06	1.02	1.37	0.03	3.41	0.25	0.72	0.1	0.13	8.84	100.43	2.09	1.22	69.30	38.60
P14	36	22.2	18.15	1.27	4.11	0.2	0.47	0.04	4.03	0.37	0.32	0.05	0.14	13.7	101.05	1.62	1.22	91.96	83.93
P15	33.8	20.3	20.5	1.34	4.3	0.26	0.41	0.04	3.78	0.83	0.49	0.06	0.14	13.65	99.9	1.66	0.99	90.99	81.98
P16	31.2	16.1	29.7	2.48	3.93	0.24	0.23	0.03	3.12	0.3	0.85	0.06	0.07	13.4	101.72	1.93	0.54	84.51	69.03
P17	36.6	16.55	22.8	2.53	2.5	0.3	0.33	0.03	3.03	0.19	0.54	0.07	0.09	14.5	100.06	2.21	0.72	83.97	67.94
P18	39.1	18.15	18.2	5.04	4.5	0.73	0.57	0.04	3.55	0.22	0.62	0.13	0.13	10.55	101.53	2.15	0.99	74.11	48.22

Continued

P19	43.2	14.15	14.6	7.99	8.92	1.78	1.22	0.05	2.78	0.19	0.9	0.14	0.09	4.82	100.84	3.05	0.96	56.28	12.57
P21	48.4	19.8	13.7	0.34	0.6	0.18	1.23	0.04	3.11	0.18	0.21	0.01	0.05	13.75	101.6	2.44	1.44	91.88	83.76
P22	43.3	23	14.55	0.19	0.51	0.13	0.99	0.04	3.28	0.15	0.19	0.01	0.05	13.5	99.89	1.88	1.58	94.61	89.22
P23	43.9	17.45	13.1	3.59	9.11	0.85	1.31	0.06	2.58	0.19	0.45	0.03	0.12	8.1	100.85	2.51	1.33	75.22	50.43
P24	44.5	18.4	13.35	1.86	5.66	0.88	1.77	0.06	2.74	0.17	0.52	0.02	0.11	10.1	100.14	2.41	1.37	80.31	60.63
P25	47.9	21.8	13.45	0.31	0.8	0.21	1.04	0.04	3.08	0.14	0.11	0.01	0.06	11.1	100.05	2.19	1.62	93.32	86.64
P26	32.8	27.4	20.2	0.1	0.61	0.03	0.14	0.03	5.08	0.13	0.13	0.01	0.02	13.35	100.04	1.19	1.35	99.02	98.05
P31	34	26	17.75	0.13	0.4	0.06	0.49	0.04	4.22	0.14	0.21	0.01	0.02	16.55	100.02	1.30	1.46	97.45	94.90
P32	32.4	26.7	18.4	0.17	0.39	0.05	0.41	0.04	4.19	0.12	0.14	<0.01	0.02	16.55	99.58	1.21	1.45	97.69	95.39
P33	34.2	26	17.7	0.33	0.89	0.15	1.18	0.059	4	0.11	0.16	0.01	0.05	14.25	99.09	1.31	1.46	94.000	88.00

The ratios of Chemical Index of Alteration (CIA) and Mafic Index of Alteration (MIA) are very high (Figure 9). These contents decrease from the surface to the depth. The alteration index and the degree of maturity are low in the fragmentary levels consisting mainly of fragments of less altered rocks.

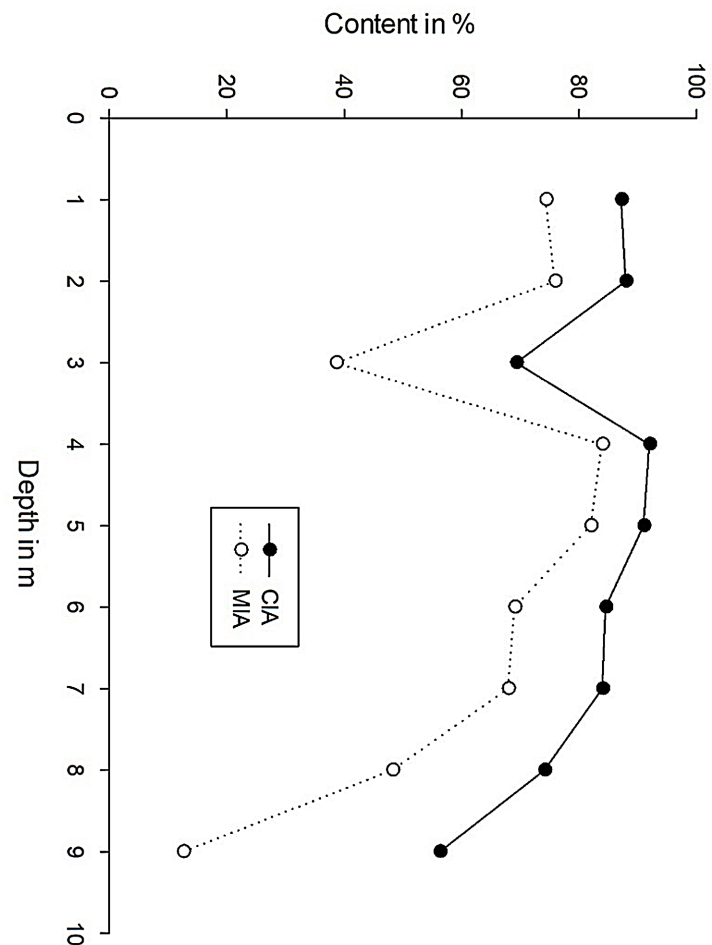


Figure 9. Variation of MIA and CIA as a function of depth.

The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio is between (1 - 3), this value increases with depth. It appears that the surface horizons and the lower horizons have ratios greater than 1, which is favorable to the formation of kaolinite and gibbsite.

The $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ ratio is greater than 1 in the surface horizons, which is characteristic of an aluminous environment in which minerals such as kaolinite, gibbsite, boehmite and diasporite develop. While this ratio is less than 1 in the lower horizons, which is symptomatic of a ferruginous environment where iron oxides and oxyhydroxides crystallize.

The distribution of the samples in the triangular digraph $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-Fe}_2\text{O}_3$ of Schellmann (1981) shows that the majority of the samples are in the center of the triangle. Generally, the soil samples are located in the center of the $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-Fe}_2\text{O}_3$ triangular diagram which is characteristic of the kaolinization or weak lateritization zone. It allows to determine the degree of lateritization and to appreciate its proximity to the aluminous, ferruginous or siliceous poles. The $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-Fe}_2\text{O}_3$ ternary diagram shows that the samples are located in the kaolinization and weak lateritization zone (Figure 10).

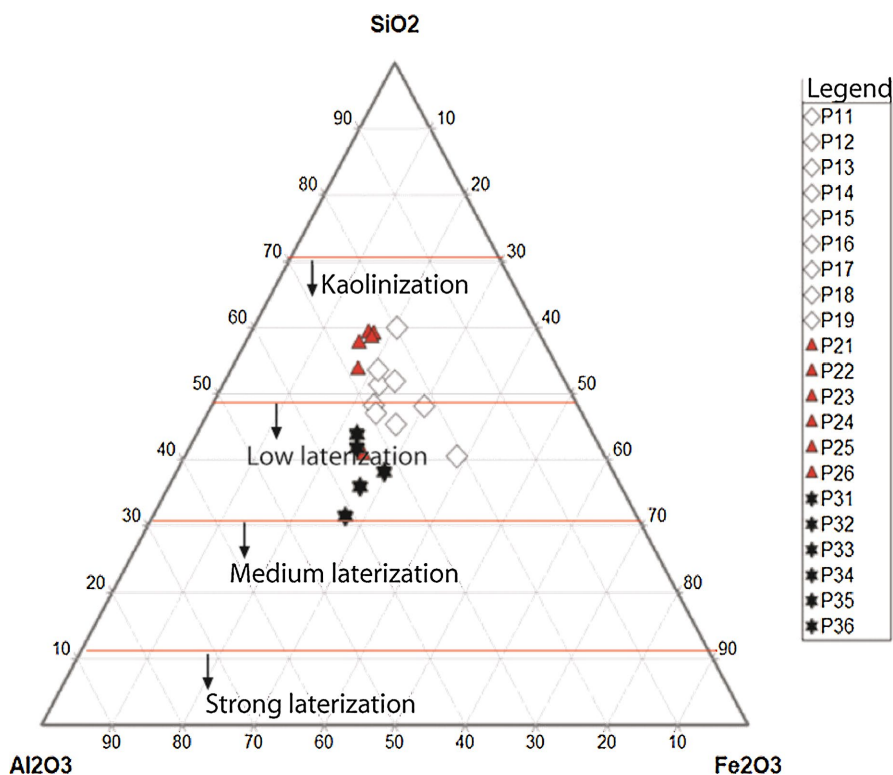


Figure 10. $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-Fe}_2\text{O}_3$ Triangular Diagram of the Sequence.

4. Discussion

4.1. Morphology and Physicochemical Characteristics of the Studied Soils

The Darang soils are part of the soils of one of the major volcanic regions of Cameroon (Adamawa plateau). This plateau has been the site of several volcanic activ-

ities which are at the origin of its current modeling. The soils of the volcanic regions of Cameroon have been the subject of studies by several authors: (Segalen, 1967; Martin, 1966, 1970; Lefèvre, 1967; Eno Belinga, 1966, 1968, 1972; Muller, 1987; Nath et al., 2000; Nguetnkam et al., 2003, 2007, 2011, 2014, 2020; Adoulko et al., 2021). The morphology of the soils of Darang shows two large sets of horizons of unequal volumes. A thick set formed on granites, surmounted by a less thick set (about 3 m) formed on recent basaltic materials (Figure 11).

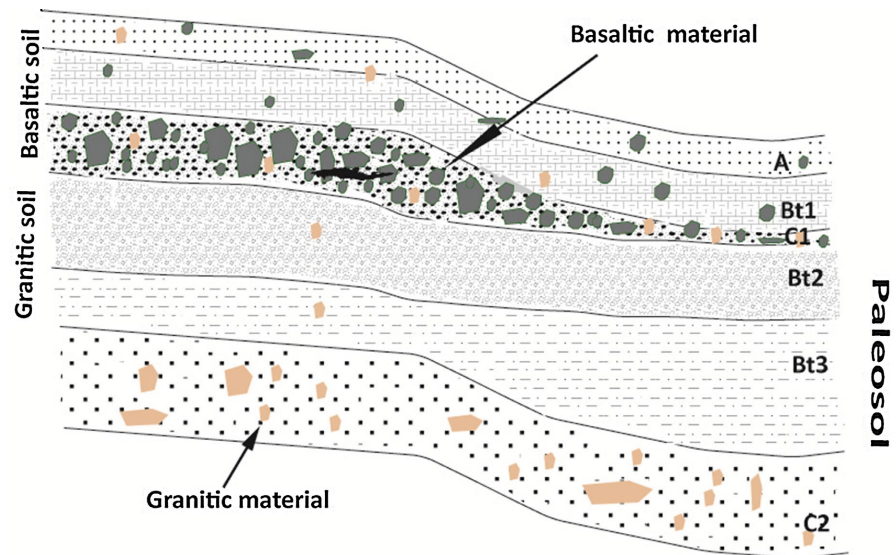


Figure 11. Morphological sketch of the soils from Northwest of Ngaoundere which showing a paleosol.

This morphology is similar to that described by Nguetnkam et al. (2020) in the Mangoli locality. They are most often found in volcanic areas of hot and humid regions, where weathering is very intense (Bitom, 1988; Tardy et al., 1993; Nguetnkam et al., 2020). The surface horizons are less thick, with a depth of more than one meter, brown overall, lumpy to polyhedral, very clayey with a few rare fragments of granites and/or basalts. They are separated from the underlying horizons by a fragmentary horizon. The fragmentary horizon which constitutes the transition with the lower part is made up of basalts and a few rare fragments of more or less weathered granites. The underlying part is the thickest, reddish brown to red, polyhedral, very clayey and compact. These soils are characteristic of the ferralsols generally described in Adamawa (Nguetnkam et al., 2003; Souaibou et al., 2015). The studied soils are strongly acidic to weakly acidic to neutral (5.2 - 7.1) from the surface to the depth (Adoulko et al., 2021).

The pH varies from 5.2 to 6 in the upper part less than 1 m, it decreases slightly, to finally increase again towards the depth where it reaches more than 7. This acidity of the surface soils could be due to agricultural activities which lead to the loss of surface elements and the contribution of chemical fertilizers. The texture of the horizons of the soils studied is generally clayey. The clay content increases with depth, to decrease slightly towards the parent rock. The clay and silt content

evolves antagonistically to silica. The C/N ratio is less than 25% in the surface horizons and greater than 25% in the deep horizons. These ratios could be explained by the fact that the organic matter is poorly decomposed on the surface and well decomposed at depth. The same is true for the saturation rate, it is less than 20% in the surface horizons and greater than 60% in the deep horizons. This means that the studied soils are undersaturated on the surface and oversaturated at depth (Adoulko et al., 2021).

4.2. Mineralogy and Geochemistry of the Studied Soils

The mineralogical processes determined by X-ray diffraction present on the one hand the primary minerals (quartz and feldspars) which are not very abundant, well crystallized and present in all the horizons of the different soil profiles. On the other hand, the predominant neoformed or secondary minerals consist of gibbsite, kaolinite, goethite and hematite. These secondary minerals are mainly kaolinite, goethite and gibbsite. The predominance of secondary minerals over primary minerals in alteration products would result from a high degree of alteration (Nguetnkam et al., 2020). The pedogenetic processes responsible for the formation of these secondary minerals are allitization and monosiallitization (Odigui Ahanda et al., 2019; Nguetnkam et al., 2020).

Geochemical data from the studied soils reveal that they have a high content of silica (SiO_2), alumina (Al_2O_3) and iron (Fe_2O_3), while the alkali and alkaline earth contents are relatively low. The silica content evolves antagonistically compared to alumina (Al_2O_3) and iron (Fe_2O_3). Under the environmental conditions described above, kaolinite and gibbsite are the quantitatively more abundant secondary minerals. The presence of gibbsite in these soils would come from feldspars, especially in environments with excellent silica evacuation conditions (Harrison, 1933; Hardy & Rodrigues, 1939; Bonifas, 1959; Millot & Bonifas, 1955; Le-neuf & Pinta, 1959; Tardy, 1969). Generally speaking, the silica content decreases with depth in favor of alumina and iron. SiO_2 is negatively correlated with Fe_2O_3 , Al_2O_3 , MnO and TiO_2 during weathering.

This could explain the fact that these elements do not concentrate in the same mineral phases. Moreover, during weathering, Fe, Al, Ti and Mn are remobilized in secondary minerals and oxyhydroxides, while silica is leached, even as a small part remains in the primary mineral phases. The leaching and mobility of elements such as alkalis and alkaline earths are proportional to the degree of weathering (Nguetnkam et al., 2020). The degree of leaching of these elements from the rock increases with the degree of weathering. This could be explained by the high content of alkalis and alkaline earths in fragmentary horizons. Silica is positively correlated with alkalis and alkaline earths.

The CIA and MIA clearly show that the studied soil profiles are made up of two major groups. An upper part formed on recent basalt and a lower part (paleosols) formed on ancient granitic rocks. The alteration index and the degree of alteration show that there is a break at one level of the profile; the degree of maturity of the

materials is discontinuous; the break zone is characterized by a high rate of alkalis and alkaline-earths.

According to Goldich (1938), Potter & Pettijohn (1963), and Nesbitt & Young (1982), the $\text{SiO}_2/\text{TiO}_2$ ratio is a fundamental geochemical indicator in pedology for assessing the intensity of chemical weathering and soil maturity. Its interpretation is based on the difference in mobility between silica and titanium during the soil formation process. Silica is considered a mobile or semi-mobile element. Under the influence of precipitation and the hydrolysis of primary minerals, silica is progressively dissolved and removed from the soil profile, while titanium is an extremely immobile element. Titanium generally remains trapped in the soil as resistant minerals. A high ratio (young/slightly weathered soil) indicates that the silica content is still close to that of the parent rock, and the soil has undergone little leaching. Conversely, a low ratio (old/highly weathered soil) indicates that a large portion of the silica has been leached, while the titanium has concentrated through residual accumulation. The soils of northwest of Ngaoundere exhibit a low $\text{SiO}_2/\text{TiO}_2$ ratio, typical of tropical soils (ferralsols) that are very old and have undergone intense weathering under a hot and humid climate (Potter & Pettijohn, 1963; Nesbitt & Young, 1982). In addition to indicating weathering, this ratio reflects a lithological discontinuity. A sharp change in the $\text{SiO}_2/\text{TiO}_2$ ratio between the second and fourth horizons indicates a change in material, specifically the deposition of basaltic materials.

5. Conclusion

The soils of Darang are composed of two levels of organization: 1) in the upper part of the profiles, the soils formed on recent basaltic materials are brown to gray in color, very clayey with a lumpy to blocky structure, they have an acidic to strongly acidic pH, with low contents of exchangeable bases, CEC and saturation rate. This part rests directly on the soils formed on granites. 2) in the lower part (the paleosols), formed on ancient granitic materials dark brown to red in color, clayey with a blocky structure. The soils have a weakly acidic pH to neutral pH with moderately high contents of exchangeable bases, CEC and saturation rate. These soils have varying textures along a sequence; however, they soils have a very clayey texture; the pH is strongly acidic to weakly acidic and/or neutral (4.3 - 7.1). Organic matter is poorly decomposed at the surface ($C/N < 25$) and well decomposed at depth ($C/N > 25$); poorly saturated at the surface (12.88% - 43%) and supersaturated at depth (>60%). Geochemically, the SiO_2 content is high (28% - 48%) and decreases with depth, while the Al_2O_3 and Fe_2O_3 concentrations are medium and vary respectively between (14% - 31%) and (13% - 29%) and increase with depth. The alteration index and the degree of maturity of the materials (CIA, MIA) show that the alteration is intense and varies discontinuously along the profiles. Nevertheless, the alteration is weak to moderate in the intermediate zone with high alkali and alkaline earth contents. Mineralogically, analyses reveal the presence of minerals such as quartz, feldspar, kaolinite, gibbsite, goethite and

hematite. The crystallochemical processes highlighted in the formation of these minerals are: monosiallitization, allitization and ferrallitization.

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Conflicts of Interest

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

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