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Characteristics, Source Area-weathering, Sedimentary Processes, Tectonic Setting and Taxonomy of Vertisols Developed on Alluvial Sediments in the Benue Trough of North Cameroon

Primus Azinwi Tamfuh[1,2,*], Jean Pierre Temga[3], Emile Temgoua[1], Emmanuel Djoufac Woumfo[4], Philemon Zo'o Zame[3], Milan Stafford Tchouatcha[5], Georges Martial Ndzana[1], Dieudonné Bitom[1], Veronique Kamgang Kabeyene Beyala[6]

[1]Department of Soil Science, Faculty of Agronomy and Agricultural Sciences, University of Dschang, P.O. Box 222 Dschang, Cameroon
[2]Department of Mining and Mineral Engineering, National Higher Polytechnic Institute, University of Bamenda, P.O. Box 39 Bambili, Cameroon
[3]Department of Earth Sciences, Faculty of Science, University of Yaoundé I, P.O. Box 812 Yaoundé, Cameroon
[4]Department of Inorganic Chemistry, Faculty of Science, University of Yaoundé I, P.O. Box 812, Yaoundé, Cameroon
[5]Department of Earth Sciences, Faculty of Science, University of Dschang, P.O. Box 67 Dschang, Cameroon
[6]Department of Earth Sciences, Higher Teacher Training College Bertoua, University of Ngaoundéré, P. O. Box 652, Cameroon
*Corresponding author: aprimus20@yahoo.co.uk

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Abstract Although Vertisols have been highly documented owing to technological breakthroughs, numerous aspects are still not fully understood such as implication of geochemistry on source area-weathering, provenance, tectonic setting and sedimentary processes as well as problems of classification and management. This work aims to highlight the geochemical characteristics of Vertisols formed on alluvial deposits in the Benue Basin of North Cameroon and to highlight their source area-weathering, sedimentary processes, tectonic setting, taxonomic level and possible management strategies. The work was done in the field and in the Laboratory. The main results showed that smectite is the predominant clay mineral. Chemical composition revealed high Si, Al and Fe contents. Heavy minerals contents are of plutonic (augite, aegerine and aegerinic augerinic augite), metamorphic (kyanite, sillimanite and andalusite) and volcanic (tourmaline) origin. This agrees with the Al_2O_3/TiO_2 ratio of 8.72 to 30.40 reflecting sediments from felsic rocks and minor mafic rocks. The CIA (chemical index of alteration: 70 to 85), PIA (plagioclase index of alteration: 66 to 82) and Ruxton's index (SiO_2/Al_2O_3: 2.27 to 3.55) suggest a warm and humid climate during moderate to intense chemical weathering probably prevailing during a more humid pre-depositional period. The K_2O/Na_2O ratio <1 suggests high sediments chemical maturity. The predominance of angular quartz grains suggests short fluvial transport distance and low sorting. The tectonic setting discrimination ternary diagram indicates that alluvial sediments, parent material of Vertisols, originate from an Active Continental Margin while the discriminant function-based multidimensional tectonic diagram indicates an arc-collisional setting suggesting that parent materials are from the Pan-African basement of the Central African Fold Belt. The Vertisols are classified as Ustic Haplusterts Clayey Isohyperthermic (United States Department of Agriculture) and as Gleyic Stagnic Vertisols (Pellic, Hypereutric, Clayic) (World Reference Base for Soil Classification).

Keywords: *Vertisols, smectite, geochemistry, tectonic setting, taxonomy, Benue Trough, North Cameroon*

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1. Introduction

During the past fifty years, ground-breaking contributions have fostered the understanding of the pedogenesis and evolution of Vertisols [1,2]. They include high-resolution micromorphology, mineralogy, geochemistry and age-control data [3,4]. Such up-to-date data have enabled the appreciation of clay illuviation, development of microstructures and vertical cracks in Vertisols as controlled by Smectite mineralogy. Vertisols are now known to form under different climates and cover 3.16 million km^2 (2.42%) of ice-free land including 47% in the tropics, 52% in the temperate zone and 1% in the boreal zone [5]. The intensity of pedoturbations in Vertisols is now known to be lower as earlier reported [6], meanwhile soil mass lateral shearing due to shrink–swell processes play the decisive function in formation of vertic features [1,2]. Spatial variability is now considered as typical of Vertisols in relation to variability in the soil moisture regime [1]. Thus, Vertisols are now included as an independent taxon of a high hierarchical level in all modern soil classification systems. The recently described high diversity in Vertisols is conditioned by a spatial and temporal variability in the course of their evolution [6]. Some of the initial criteria for the Vertisol identification and classification (opening/closure of cracks, gilgai microrelief, some quantitative limits on the shrink–swell potential and the duration of the open state of cracks) have been changed. Specifically at sub-order level, Vertisols are differentiated based on soil moisture and temperature conditions and the duration of the open state of soil cracks is also considered [5]. Although, Soil Taxonomy presents a clear distinction of Vertisols, it fails to include the notion of Vertic horizon as a diagnostic horizon of Vertisols. In recent years, the problem of the applicability of the pedon concept to Vertisols has been raised as related to a considerable microvariability in soil properties within a pedon of Vertisols as defined in Soil Taxonomy [7]. Recent findings helped to decode climate change-related pedogenic processes during the Holocene and how they contributed to modify soil properties in the course of time [8]. Up to date, many authors have reported the nature and genesis of Vertisols [9], their chemistry and mineralogy [10,11], engineering properties [12], agricultural potential [13] and surface properties [14,15]. Nevertheless, in-depth knowledge of numerous aspects of Vertisols characteristics is still lacking at site-specific scale. In North Cameroon, Vertisols occupy more than 1,200,000 hectares of land [16]. Despite the numerous studies conducted on Vertisols in this area [9,11,17,18], many questions still require answers to better understand these soils: (1) what are the specific geochemical features of these Vertisols? (2) What is the implication of these geochemical properties to the understanding of weathering, provenance and sedimentary processes of these soils? (3) to which taxonomic group can these Vertisols be referred to? (4) What are the best management strategies of these Vertisols when put to use? The main objective of this work is to characterize the Vertisols formed on alluvial sediments in the Benue Basin of North Cameroon and to constrain their source area-weathering, sedimentary processes, tectonic setting, taxonomic level and management strategies. This study provides additional information on the evolution processes, taxonomic level and management strategies of the Benue Basin Vertisols of North Cameroon. The study´s interest is both fundamental and applied, to permit sustainable management and exploitation of these soils.

2. Geographical and Geological Setting of the Benue Basin

The Benue Basin in North Cameroon is under a tropical climate with two contrasted seasons: a humid climate from May to October, and a dry climate from November to April. This is a Classical Sudanian climate [19], with mean annual precipitation range of 900 to 1500 mm and mean annual temperature of 28°C. The vegetation is the Sudanian Savannah, characterised by the Sudano-Sahelian seasonally flooded prairie inside the Benue floodplains, the altitude Sudanian Savannah in the Mandara Mountains and the scanty wood savannah covering the rest of the landscape [20]. The major soils are Inceptisols/Regosols, Gleysols, Oxisols, Vertisols, Solonchaks, Alfisols and Luvisols [16]. Streams, mainly seasonal, originate either in the north (Mandara Mountains) or south (Adamawa Highlands). The main River, the Benue, takes its source in the Adamawa Mountains; the drainage pattern is dense and dendritic pattern. The Benue River Basin is found at the centre of the Benue trough (Figure 1). This trough is a tectonic structure that extends from the Niger Delta to North Cameroon for a distance of more than 1000 km and constitutes the Yola branch [21,22]. It is filled with sedimentary rocks (Middle to Upper Cretaceous sandstones) which are intruded by Tertiary volcanics (trachyte, basalts, hawaiites, mugearites, rhyolites and phonolites) [23]. The basement rock is granite-gneissic underlying the sandstones [24]. The Cretaceous sandstones are overlain by a 35 m thick alluvial terrace composed of a recent <3.000 years BP unconsolidated sandy silty clays and an old ~11000 years BP terrace [25]. The studied site characteristics are compiled in Table 1.

3. Field and Laboratory Methods

Five Vertisol profiles were selected (P_1 in Garoua, P_2 in Bounguel, P_3 in Badoudi, P_4 in Poumpoumré and P_5 in Karewa) for detailed study, based on depth above the water table and accessibility. The morphological organization of P_1, P_3 and P_5 is shown in Figure 2. The individual profiles were described, georeferenced and sampled at different depths. Profile P_1 shows four principal horizons (Figure 2): a grey (10YR5/1) surface horizon (A1), a dark grey (10YR4/1) horizon with slickensides (B_1), very dark grey (10YR3/1) massive horizon (B_{21}) and a very dark grey (10YR3/1) horizon (B3g). The surface A1 horizon is 30 cm thick with about 10% yellowish red patches and 20% voids. Surface cracks separating blocks (20-100 cm diameter) define a polyhedral macrostructure. Transition with the underlying horizon is gradual, marked by the desertion of cracks, emergence of slickensides and light darkening of soil colour. The B_1 horizon is characterized by many smoothed shiny surfaces called slickensides. Transition to the next horizon is very gradual, marked by the disappearance of slickensides. The B_{21} horizon is clayey and massive compact, with 5% reddish yellow (7.5YR6/8) patches. The transition to the underlying horizon is gradual, marked by intensification of the darkness in colour. The B_{3g} horizon is clayey and compact, with massive structure, 5% reddish yellow (7.5YR6/8) patches. The rest of the profiles (P_2, P_3, P_4 and P_5) are morphologically similar to P1.

In the laboratory, geochemical, mineralogical, physico-chemical, morphoscopic and heavy mineral analyses were performed. The geochemical and mineralogical analyses were done in the “Centre de Recherche Pétrographique et

Géologique" of Nancy (France). The physical and physico-chemical analyses were done in the Laboratory of Physico-chemistry of Mineral Materials (University of Yaoundé I, Cameroon) and at the International Institute for Tropical Agriculture of Nkolbissong (Yaoundé, Cameroon).

For mineralogical and chemical analyses, soil samples were air-dried and then crushed into <0.2 mm fine powder. The mineralogical analysis of the soil samples was done by X-ray diffraction using a 2080 sigma diffractometer (BRUKER type), equipped with a Ni-filter and a Cu anode (quartz mono-chromator, K-alpha 1 wavelength=1.5418 Å; scanning range: 5-70°; drive axis = 2θ; scanning speed=0.002°/s). The semi-quantitative mineral composition from the X-ray patterns was done by Rietveld refinement technique [26]. The presence of smectite was detected by the ethylene glycol test [27]. The geochemical analyses of the major elements were done by Inductively Coupled Plasma-Atomic Emission Spectrometry (Thermo Fischer ICap 6500 mark), after fusion in $LiBO_2$ and dissolution in Nitric acid. Instrumental relative errors for major elements are less than 3%.

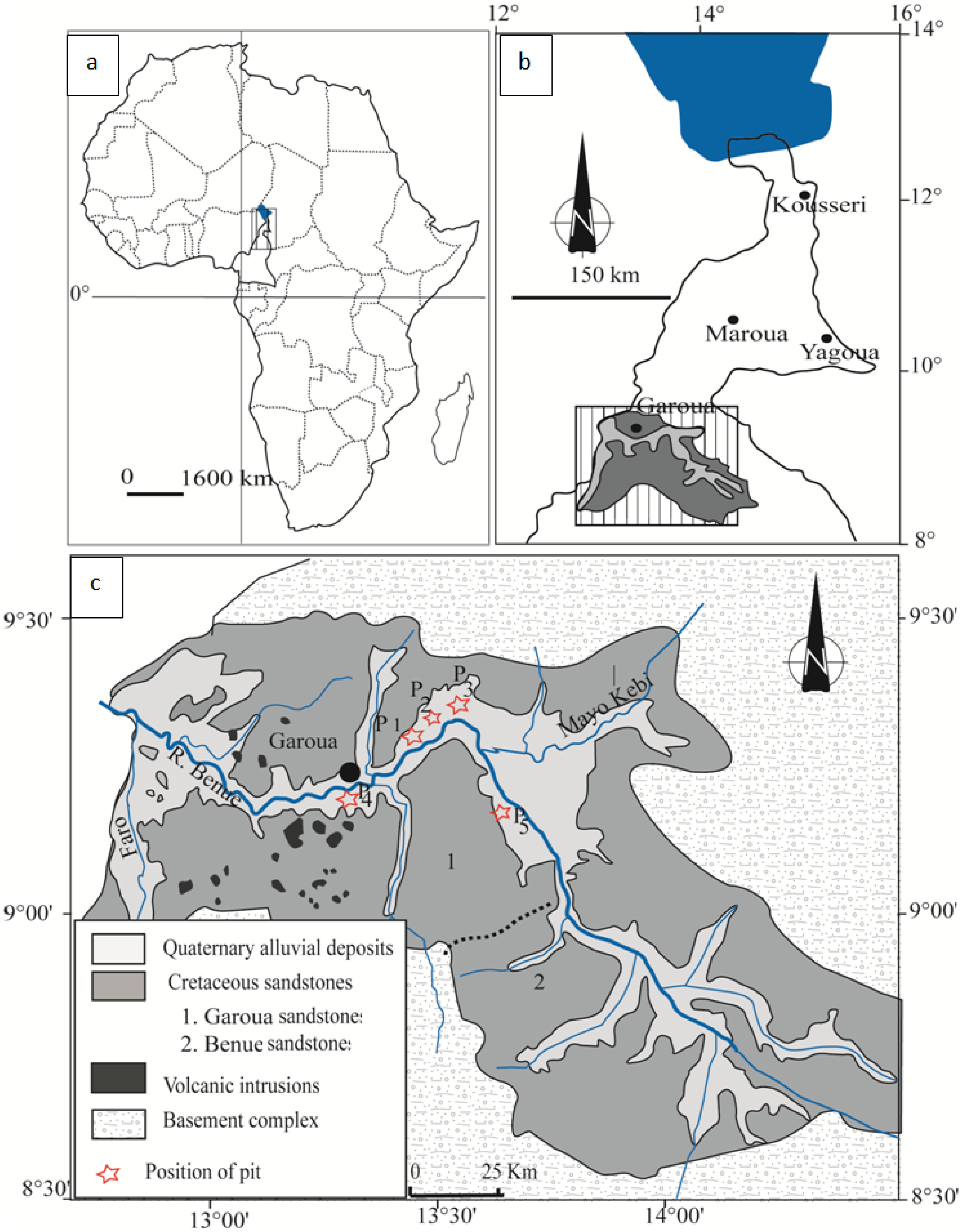

Figure 1. Location and Geology of the studied area. (a) Map of Africa locating North Cameroon; (b) Map of North Cameroon locating the Benue Trough; (c) Geological map of the Benue Trough (modified from [21]) and position of pits

Table 1. Characteristics of the studied site

Characteristics	Garoua	Poumpoumre	Bounguel	Badoudi	Karewa
Geographic coordinates	9°15′N, 13°24′E	9°20′N, 13°28′E	9°24″ N, 13°31′ E	10°13′36″ N, 13°34′28″ E	09°11′34″ N, 13°20′59″ E
Mean altitude	175 m	180 m	178 m	174 m	191 m
Climate	Classical sudanian savannah	Classical Sudanian savannah	Classical Sudanian savannah	Classical Sudanian savannah	Classical Sudanian savannah
Parent material	Recent alluvium	recent alluvium	Recent alluvium	Recent alluvium	Recent alluvium
Landform	Horizontal alluvial floodplain with sandy levees and meanders on ancient terrace	Horizontal alluvial floodplain with sandy levees and meanders on ancient terrace	Horizontal alluvial floodplain with sandy levels and meanders on ancient terrace	Horizontal alluvial floodplain with sandy levels and meanders on ancient terrace	Horizontal alluvial floodplain with sandy levels and meanders on ancient terrace
Surface aspect	Desiccation cracks, numerous termite mounds	Desiccation cracks	Desiccation cracks	Desiccation cracks, numerous termite mounds and worm casts	Desiccation cracks, numerous termite mounds and worm casts
Natural vegetation	Seasonally flooded prairie	Seasonally flooded prairie	Steppe	Seasonally flooded prairie	Seasonally flooded prairie
Drainage	Very poor	Poor	Very poor	Poor	Very poor
Slope gradient (%)	< 1	< 1	< 1	< 1	< 1
Erosion marks	Low	Low	Low	Low	low
Land use	Millet cultivation	Millet cultivation	Fallow	Five year fallow	Pluvial/irrigated rice cultivation

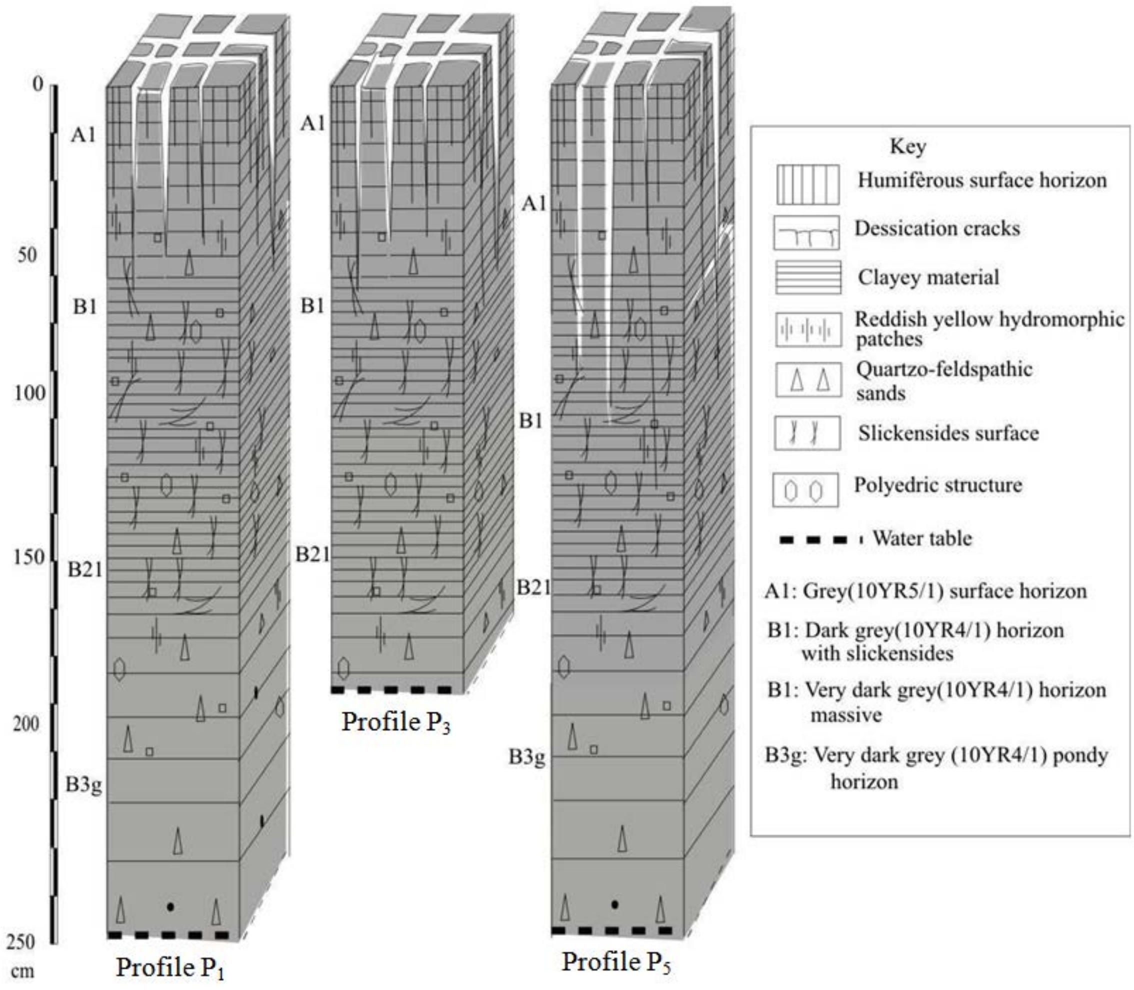

Figure 2. Morphological view of three Vertisol profiles (P_1, P_3 and P_5) studied in the Benue Basin of North Cameroon

Three weathering indices were calculated from the soil geochemical composition and used to characterise their weathering state: Ruxton Ratio (R) of [28], Chemical index of alteration (CIA) of [29] and Plagioclase index of alteration (PIA) of [30] corresponding to equations (1), (2) and (3), respectively.

$$R: SiO_2 / Al_2O_3 \qquad (1)$$

$$CIA: \left(Al_2O_3 + K_2O\right) / \left(MgO + CaO + Na_2O\right) \qquad (2)$$

$$PIA: \frac{(100)\left[\left(SiO_2 / TiO_2\right)\right]}{\left[\left(SiO_2 / TiO_2\right) + \left(SiO_2 / Al_2O_3\right) + \left(Al_2O_3K_2O\right)\right]} \qquad (3)$$

CaO* represents the CaO contained only in the silicate fraction and is corrected for carbonate and apatite content.

It is based on the assumption for CaO* that the molar CaO/Na_2O ratio of silicates is not higher than one. As the molar CaO content (corrected for apatite) was less than the molar Na_2O content, the value was taken as CaO*. On the other occasions, the CaO content of silicates was supposed to be equivalent to the molar Na_2O content [31].

The soil physical and chemical analyses were performed according to the procedures described by [32]. The particle size distribution was measured by Robinson´s pipette method. The pH-H_2O was determined in a soil/water ratio of 1:2.5 and pH-KCl in a soil/KCl ratio of 1:2.5 using a glass pH-meter. The organic carbon (OC) was measured by Walkley-Black procedure. Total nitrogen (TN) was measured by the Kjeldahl method. Exchangeable bases were dosed by ammonium acetate extraction method buffered at neutral pH, then measured by atomic absorption spectrometry. The cation exchange capacity (CEC) was measured by sodium saturation method. Available phosphorus (P) was dosed by concentrated nitric acid reduction method.

The soil organic carbon stock (SOCS) and total soil organic carbon stock (TSOCS) were respectively calculated based on equations (4) and (5), in reference to [32]:

$$SOCS\left(Mg.ha^{-1}\right) = \left(OC\ x\ BD\ x\ d\ x\left(1-\delta_{2mm}\%\right) x\,10\right) \quad (4)$$

$$TSOCS\left(Mg.ha^{-1}\right) = \sum_{horizon} SOCS \quad (5)$$

Where OC is the organic carbon content (g kg^{-1}), d stands for soil layer thickness (m), and δ2mm represents percentage coarse fraction (ϴ>2mm) and BD is the soil bulk density (Mg m^{-3}).

The separation of heavy minerals was performed in a decantation bulb having bromoform (density=2.9 g/cm^3). Heavy minerals were washed with alcohol and warm dilute HCl acid, oven-dried and mounted on glass thin slides for microscopic observations. Morphoscopic analysis involved the observation of 50 randomly selected sand-sized quartz grains with a binocular lens.

4. Results

4.1. Mineralogy of the Vertisols

The X-ray diffractograms show that all the Vertisol samples display principal peaks at 15.5 Å, 4.48 Å and 1.67 Å (Figure 3). Ethylene glycol treatment of horizon of A1 (0-30 cm of P_1) enables to note a displacement of peak 15.5 Å to 17.75 Å (Figure 4) confirming the presence of smectite. Kaolinite is identified by its main peaks at 7.15 Å, 3.58 Å and 2.16 (Figure 3; Table 2). The other minerals present in smaller amounts in the Vertisols are illite (10 Å, 2.56 Å), feldspars and quartz (4.25 Å, 3.34 Å and 1.62 Å), goethite (2.68 Å, 1.49 Å) and ilmenite (3.72 Å, 2.38 Å and Å). Globally, the mineralogical composition of the Vertisols is such that Smectite> (44.86 to 60.59%) > kaolinite (12.30-20.30%)> quartz (9.88-17.45%) > feldspars (4.55-10.27%) > illite (2.05-6.53%), ilmenite (2.16-4.92%) > goethite (0.27-2.12%) (Table 2).

4.2. Geochemistry and Weathering Indices of the Studied Vertisols

The major elements are grouped into two categories based on their relative abundance: the less abundant elements with concentrations below 0.5% (P_2O_5, MnO_2) and more abundant elements with concentrations greater than or equal to 0.5% (SiO_2, Al_2O_3, Fe_3O_3, TiO_2, CaO, MgO, K_2O, Na_2O) (Table 3). Si (50.35 to 59.23% SiO_2) is the most abundant element in all the Vertisols horizons. Profile P_4 shows the highest Si contents while P_1 reveals the lowest concentrations. Aluminium is the second most represented element in the studied Vertisols, varying from 16.52% Al_2O_3 to 21.61% Al_2O_3. The aluminium concentration varies mildly with depth and from one profile to the other. Fe contents (4.80%-7.91% Fe_2O_3) are lower than those Al and Si. The Fe_2O_3/K_2O ratio ranges between 2.67 and 7.80 while the Al_2O_3/Fe_2O_3 varies from 0.26 to 0.39 (Table 3). The SiO_2–Al_2O_3–Fe_2O_3 ternary diagram reveals a predominant siliceous aluminous composition (Figure 5a). The Ti contents vary from 0.68% to 2.46% TiO_2. The alkaline (Na and K) and alkali-earth (Ca and Mg) elements are well represented all the profiles. K is the most abundant basic cation with contents varying from 1.0% to 3.22% K_2O. Mg contents vary from 0.98 to 2.8. Ca is the third most represented basic cation (0.21.68% to 1.68% CaO). Na is the least represented base (0.50 to 1.47% Na_2O). The Mn and P contents are very low, (0.03 to 0.11% MnO and <0.001 to 0.21% P_2O_5, respectively). The loss on ignition (LOI) varies from 8.88% to 14.64. The Ruxton's ratio (Si/Al ratio) ranges from 2.27 to 3.55 (Table 3). The CIA values range from 70.36 to 84.95 while the PIA values vary from 66.09 to 81.75. The Al_2O_3–(CaO+Na_2O)-K_2O ternary diagram (Figure 5b) of Nesbitt and Young (1982) shows that the Vertisols are moderately to intensely weathered. The tectonic setting discrimination ternary diagram (Figure 6a) of Kroonenberg [34] enables to note that all the Vertisol samples fall in the field of active continental margin. Also, the Na_2O-CaO-K_2O triangle (Figure 6b) of [35] reveals that the studied Vertisols fall under the field of active continental margin and few samples plot in the continental island arc field. In Figure 6c, almost all the Vertisol horizons plot in the active continental margin and few samples fall in the passive continental margin and the continental\island arc fields. In Figure 6d, the discrimination diagram of [36] reveals that the Vertisols plot mainly in the arc field and only few samples in the collision field. There is a negative correlation between silica and basic cations as well as positive correlation between bases, silicon and weathering indices (Table 4). A significant positive correlation exists between Al, Ti and Fe while CIA, PIA and Al show a significant negative correlation. Silicon and titanium show a significant negative correlation. The CIA and PIA correlate positively with silica but negatively with Al and basic cations.

4.3. Physical and Chemical Characteristics of the Vertisols

The physical characteristics of the Vertisols are respectively compiled in Table 5. The particle density ranges from 2.5 to 2.6 g.cm^{-3} and decreases slightly with depth for some surface horizons (Table 5). The bulk density of the Vertisol horizons fluctuates between 1.8 and 2.2 g.cm^{-3} (Table 5). Those values increase with depth in all the Vertisol profiles. It decreases with depth for all the studied sites, with the A1 horizons being the most porous. The percentage moisture ranges from 6.7% to 14.42%. This moisture content globally increases with profile depth, except for P_5 where a mild decrease is noted from A_1 to B_1 before increasing towards the bottom. The particle size wise, clay is the most abundant fraction in all the Vertisol horizons, varying from 45% to a maximum of 75%. In all the profiles, the clay contents increase slightly with depth, except P_4 where a decrease is observed (Table 5). Sand is the least abundant fraction, except for B_{21} horizons of P_3 and P_5 where sand is more abundant than silt. These Vertisols show a clayey to heavy clayey texture. Coarse fragments are very low (0 to <2%).

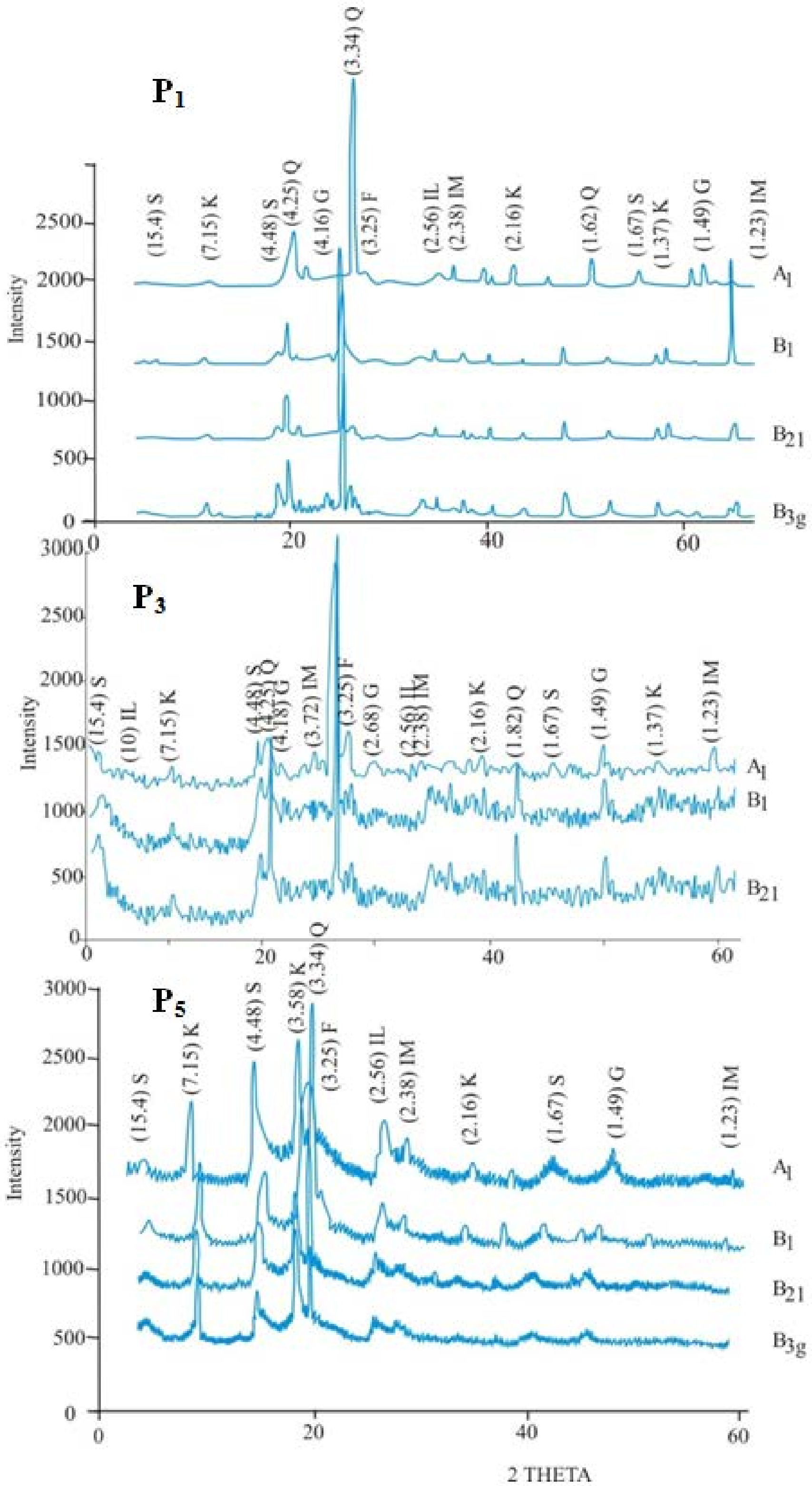

Figure 3. X-ray diffraction patterns of Vertisol horizons from Garoua (P_1), Bounguel (P_3) and Karewa (P_5). (S = smectite; = Kaolinite; IL = Illite; IM= Ilmenite; F = Feldspar; G = Goethite; Q = Quartz)

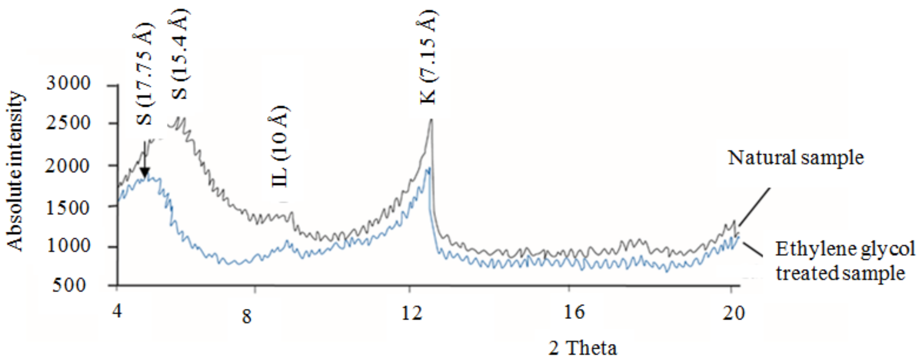

Figure 4. X-ray diffraction of the A1 horizon (0-30 cm) from the Benue Basin Vertisols after treatment with ethylene glycol (S= smectite; K= kaolinite; I = Illite)

Table 2. Semi-quantitative estimation of the mineralogical composition of the studied Vertisols

Horizon (depth in cm)	Smectite	Kaolinite	Quartz	Feldspars	Illite	Ilmenite	Goethite	S/K	K/I
Bounguel (P_1)									
A1 (0-30)	40.80	17.9	17.27	10.27	9.76	4.13	0.81	2.28	1.83
B1 (30-100)	42.86	18.57	17.43	8.57	7.14	4.29	1.43	2.31	2.60
B_{21} (100-150)	48.57	17.86	18.71	7.39	5.93	1.79	0.46	2.72	3.01
B_{3g} (150-250)	53.28	17.09	16.19	7.90	3.55	1.71	0.27	3.12	4.81
Poumpoumre (P_3)									
A1 (0-30)	53.03	20.3	12.15	7.58	3.36	3.79	0.52	2.61	6.04
B1 (30-150)	57.73	16.27	11.18	4.55	4.36	4.55	1.82	3.55	3.73
B_{21} (150-230)	62.33	15.16	10.29	5.17	2.05	3.04	2.12	4.11	7.40
Karewa (P_5)									
A1 (0-20)	49.85	16.79	11.57	9.92	6.53	4.92	0.48	2.97	2.57
B1 (20-45)	53.03	12.30	9.88	5.85	3.58	2.58	0.52	4.31	3.44
B_{21} (45-140)	60.59	16.06	11.32	5.09	3.26	2.16	0.65	3.77	4.93
B_{3g} (140-200)	57.12	16.13	12.4	6.92	2.26	4.48	0.83	3.54	7.14

S/K= smectite-to-kaolinite ratio; K/I=kaolinite-to-illite ratio.

Table 3. Chemical composition (wt% oxide) and weathering indices of the Benue Basin Vertisols of North Cameroon

Horizon (depth)	SiO_2	Al_2O_3	Fe_2O	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_3	LOI	Total	Al_2O_3/TiO_2	Fe_2O_3/K_2O	Al_2O_3/Fe_2O_3	K_2O/Al_2O_3	K_2O/Na_2O	R	CIA	PIA
Garoua (P_1)																				
A_1(0-30 cm)	53.46	18.88	6.72	0.08	1.06	1.16	0.87	1.85	1.02	0.09	14.64	99.89	18.51	3.63	0.36	0.10	2.13	2.50	79.51	74.82
B_1(30-100 m)	53.29	18.79	6.60	0.06	1.34	1.00	0.88	2.18	1.01	0.16	14.61	99.89	18.60	3.03	0.35	0.12	2.48	2.40	78.15	72.69
B_{21}(100-150 cm)	53.40	19.07	6.89	0.09	1.38	1.38	0.92	2.11	1.11	0.19	14.03	100.17	17.18	3.27	0.36	0.11	2.29	2.40	78.22	72.23
B_{3g}(150-250 cm)	53.15	20.66	7.20	0.06	1.20	1.20	0.53	1.77	1.08	0.21	13.07	99.88	19.13	4.07	0.35	0.09	3.34	2.27	84.95	78.19
Poumpoumre (P_2)																				
A_1(0-40 cm)	50.35	21.49	7.91	0.06	1.79	1.34	1.35	2.96	2.46	0.04	10.30	100.05	8.74	2.67	0.37	0.14	2.19	2.34	73.76	68.28
B_1(40-110 m)	50.81	21.35	7.69	0.11	2.44	1.35	1.47	2.51	1.51	0.15	11.10	100.49	14.14	3.06	0.36	0.12	1.71	2.38	73.87	70.61
B_{21}(110-210 cm)	51.31	21.61	7.44	0.11	2.11	1.28	1.43	2.45	1.46	0.17	11.45	100.82	14.80	3.04	0.34	0.11	1.71	2.32	74.61	71.57
Bounguel (P_3)																				
A_1(0-60 cm)	55.51	18.36	6.51	0.06	2.8	1.46	1.10	2.73	1.10	0.03	12.53	100.19	16.69	2.38	0.35	0.15	2.48	2.94	73.63	66.09
B_1(60-150 m)	52.05	19.29	5.53	0.05	2.6	1.60	1.41	3.22	1.18	<0.001	12.05	99.98	16.35	1.72	0.29	0.17	2.28	2.70	70.36	62.97
B_{21}(160-230 cm)	52.34	19.48	6.11	0.06	2.67	1.68	1.38	2.9	1.19	<0.001	12.19	100.31	16.37	2.11	0.31	0.15	2.10	2.68	71.72	65.17
Badoudi (P_4)																				
A_1 (0-30 cm)	59.23	20.67	6.03	0.03	1.54	0.31	0.56	1.87	0.68	0.2	09.73	100.51	30.40	3.22	0.29	0.09	3.34	2.86	84.25	80.31
B_1(30-60 cm)	59.22	19.2	7.55	0.04	1.59	0.86	0.64	1.67	1.31	0.01	8.88	99.99	14.66	4.52	0.39	0.09	2.61	3.08	83.07	78.36
B_{21} (60-120 cm)	58.04	20.19	7.96	0.01	1.03	1.01	1.23	1.02	1.25	0.13	8.76	100.56	16.15	7.80	0.39	0.05	0.83	2.87	79.67	81.75
B_{3g}(120-215 cm)	58.42	20.05	5.45	0.02	1.01	1.2	1.44	1.54	0.86	0.18	10.18	100.17	23.31	3.54	0.27	0.08	1.07	2.91	75.79	76.39
Karewa (P_5)																				
A_1 (0-20 cm)	55.02	16.52	4.86	0.08	0.98	0.56	0.5	1.62	1.29	0.05	12.23	99.97	12.81	3.00	0.29	0.10	3.24	3.33	82.94	77.60
B_1(20-80 cm)	57.59	16.60	5.59	0.10	1.11	0.20	0.75	1.58	0.88	0.11	11.51	100.49	18.86	3.54	0.34	0.10	2.11	3.55	79.89	78.52
B_{21} (80-140 cm)	57.32	17.82	5.18	0.05	1.07	1.04	1.32	1.38	1.04	0.13	14.12	100.50	17.13	3.75	0.29	0.08	1.05	3.21	75.36	76.29
B_{3g}(140-200 cm)	58.09	18.39	4.80	0.11	1.32	0.77	1.21	1.06	0.89	<0.001	13.74	100.30	20.66	4.53	0.26	0.06	0.88	3.16	78.19	80.87

**Correlation is significant at the 0.01 level (2-tailed); *Correlation is significant at the 0.05 level (2-tailed).

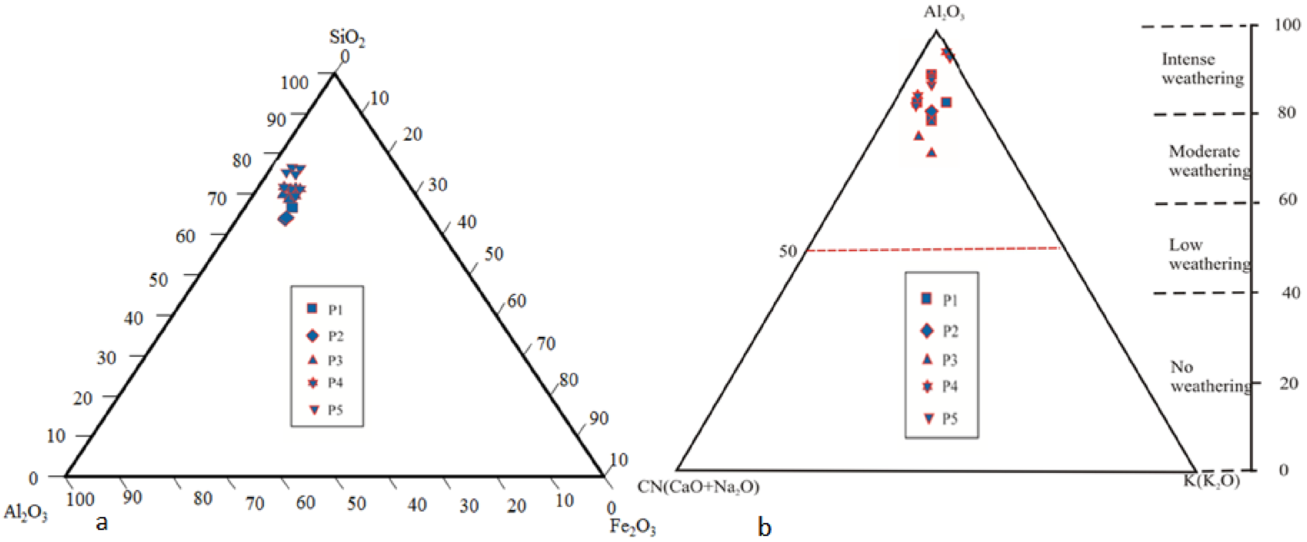

Figure 5. Triangular diagrams of geochemical data. (a) SiO_2-Al_2O_3-Fe_2O_3 triangular plot of the Vertisols; (b) Al_2O_3-(CaO^*+Na_2O)-K_2O (A–CN–K) triangular diagram illustrating the degree of chemical weathering in reference to [29]

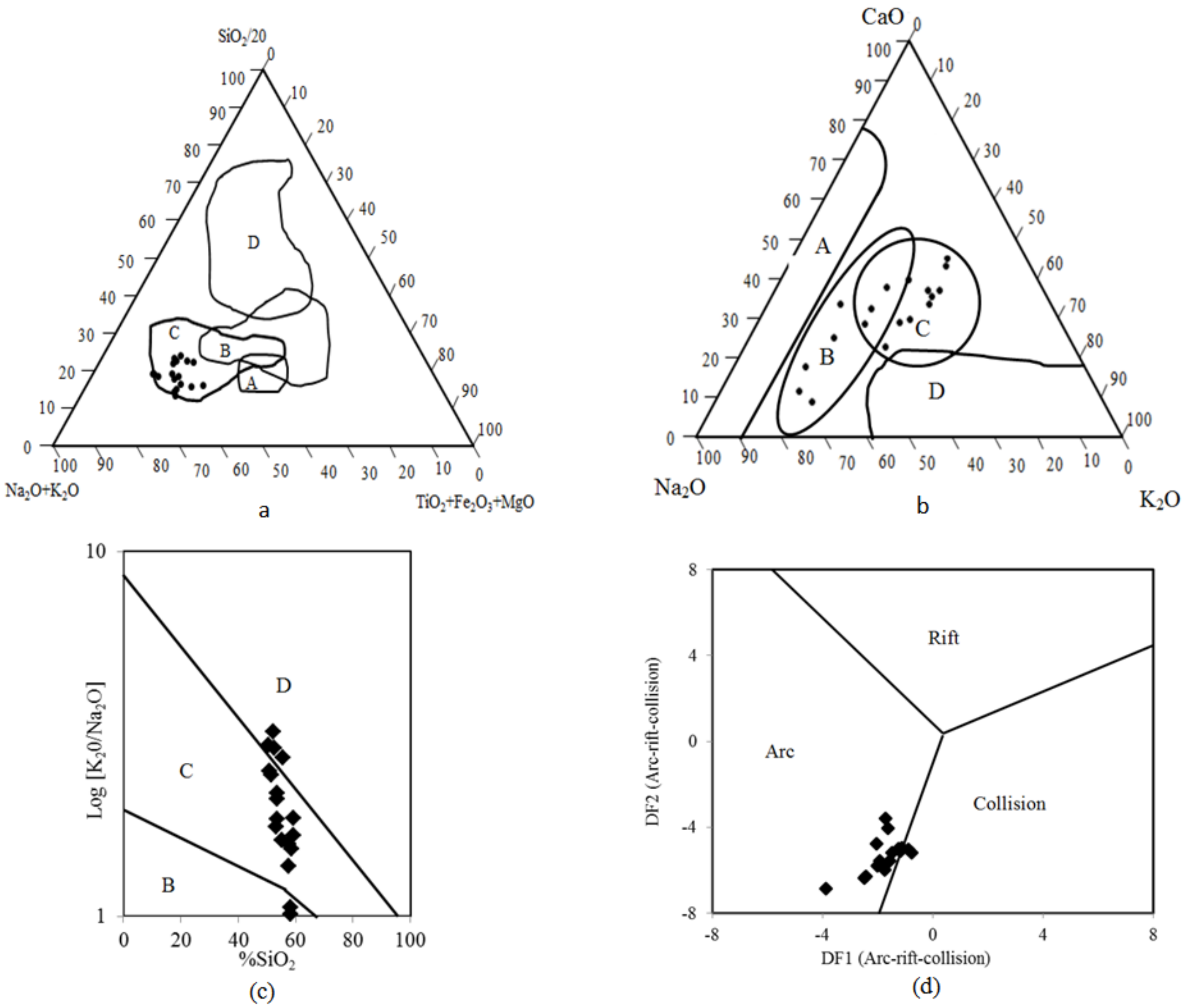

Figure 6. Tectonic setting discrimination diagrams of the Vertisols of the Benue Floodplain. Chart (a) is from [34]; (b) from [35]; (c) from [36] and (d) from [58]. DF1: discrimination function 1; DF2: discrimination function 2 (DF1(Arc-Rift-Collision)=(0.608ln(TiO_2/SiO_2)(-1.854xln(Al_2O_3/SiO_2) +(0.299ln(Fe_2O_3/SiO_2)+(-0.550ln(MnO/SiO_2)+(0.120ln(MgO/SiO_2)+(0.194ln(CaO/SiO_2)+(-1.510ln(Na_2O/SiO_2)+(1.94ln(K_2O/SiO_2)+(0.003ln(P2O5/SiO_2) + 0.294; DF2(Arc-Rift-Collision) = (-0.554ln(TiO_2/SiO_2)+(-0.995ln(Al_2O_3/SiO_2)+(1.765ln(Fe_2O_3/SiO_2) + (-1.391ln(MnO/SiO_2) + (-1.034ln(MgO/SiO_2) + (0.225ln(CaO/SiO_2)+(0.713ln(Na_2O/SiO_2)+(0.330 ln(K_2O/SiO_2)+(-0.637ln(P_2O_5/SiO_2)-3.631. A: Oceanic Island; B: Continental Island Arc; C: Active Continental Margin; D: Passive Margin)

Table 4. Correlation among major oxides, CIA and PIA (n=18)

	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_3	CIA	PIA
SiO_2	1.00											
Al_2O_3	-0.40	1.00										
Fe_2O	-0.39	0.69**	1.00									
MnO	-0.44	-0.24	-0.08	1.00								
MgO	-0.50*	0.32	0.21	0.16	1.00							
CaO	-0.66**	0.43	0.34	-0.03	0.62**	1.00						
Na_2O	-0.35	0.39	0.09	0.05	0.47*	0.64**	1.00					
K_2O	-0.76**	0.35	0.25	0.14	0.84**	0.65**	0.36	1.00				
TiO_2	-0.61**	0.48*	0.57*	0.12	0.29	0.39	0.34	0.48*	1.00			
P_2O_3	0.02	0.34	0.23	-0.06	-0.40	-0.18	-0.17	-0.27	-0.27	1.00		
CIA	0.75**	-0.76**	-0.66**	-0.10	-0.31	-0.64**	-0.24	-0.53*	-0.41	-0.36	1.00	
PIA	0.72**	-0.19	-0.12	-0.14	-0.83*	-0.78**	-0.52*	-0.94**	-0.40	0.36	0.43	1.00

**Correlation is significant at the 0.01 level (2-tailed); *Correlation is significant at the 0.05 level (2-tailed); n=sample population.

Table 5. Physical characteristics of the Vertisols of the Benue Basin of North Cameroon

Horizon (depth)	Particle density	Bulk density	Porosity	Residual humidity	Particle size distribution (%)						Rock fragments
					Coarse sand	Fine sand	Coarse silt	Fine silt	Clay	Textural Class	
	g. cm^{-3}		%	%		%					(%)
Garoua(P_1)											
A_1(0-30 cm)	2.5	1.8	28.00	6.70	4.30	6.54	11.66	15.00	62.50	Heavy clay	1.72
B_1(30-100 cm)	2.6	2.1	19.00	8.10	2.15	4.15	12.50	12.50	70.00	Heavy clay	0.00
B_{21} (100-150 cm)	2.6	2.1	19.00	9.70	4.05	2.45	8.50	8.50	72.50	Heavy clay	1.88
B_{3g} (150-250 cm)	2.6	2.2	15.40	10.30	2.70	4.80	12.50	06.36	75.00	Heavy clay	0.00
Poumpoumre (P_2)											
(0-40 cm)	2.5	1.9	24.00	7.90	7.15	3.55	8.00	14.50	68.00	Heavy clay	0.00
B_1(40-110 cm)	2.6	2.1	19.00	8.80	3.36	8.59	6.28	9.75	72.00	Heavy clay	0.00
B_{21} (110 – 210 cm)	2.6	2.1	19.00	9.30	3.84	2.56	8.22	11.78	75.00	Heavy clay	1.61
Bounguel (P_3)											
A_1(0-60 cm)	2.5	1.8	28.00	7.70	08.28	16.68	13.40	18.28	45.00	Clay	1.38
B_1(60-150cm)	2.6	2.0	23.10	7.90	07.10	22.36	09.08	14.88	47.50	Clay	1.66
B_{21} (150-230 cm)	2.6	2.2	15.40	10.80	7.79	15.10	13.08	13.30	53.50	clay	1.73
Badoudi (P_4)											
A_1(0-30 cm)	2.6	1.8	30.76	11.10	6.91	13.10	10.20	24.10	46.60	Clay	1.88
B_1(30-60 cm)	2.6	2.0	23.10	12.30	04.80	12.03	11.30	18.10	54.20	Clay	1.70
B_{21} (60-120 cm)	2.6	2.2	15.40	11.80	6.20	08.43	07.11	11.22	68.00	clay	0.00`
B_{3g} (120-215 cm)	2.6	2.2	15.40	13.25	10.03	3.34	15.12	12.25	58.26	Heavy clay	1.77
Karewa (P5)											
A_1(0-20 cm)	2.6	2.0	23.10	11.10	6.02	11.12	08.09	16	59.50	Clay	1.79
B_1(20-80 cm)	2.6	2.0	23.10	10.30	09.00	14.01	06.80	11.30	60.50	Heavy clay	1.60
B_{21} (80-140 cm)	2.6	2.2	15.40	11.80	05.51	08.02	06.10	15.60	66.75	Heavy clay	1.81
B3g (140-200 cm)	2.6	2.2	15.40	13.42	03.40	09.30	11.11	05.00	72.50	Heavy clay	1.73

Soil chemical properties are presented in Table 6. The soil pH-H_2O ranges from 5.6 to 7.4. Except for P_1, pH-H_2O is slightly lower at the surface and increases slightly with depth. The pH-KCl is less than pH-H_2O for all the profiles and ranges between 4.8 and 6.4; it generally increases with depth in all the profiles, except for profile P_1 where an opposite trend is observed. The pH-KCl values also increase with depth in all the Vertisols profiles, but for P_1. The exchangeable acidity (ΔpH) ranges between 0.8 and 1.3 and varies irregularly with depth in all the profiles, but for P_2 where values decrease depth-wise. The OC content ranges from 0.26 to 2.62% dry mass (Table 6). The values are higher at the surface than at the sub-surface, where a sharp decrease is observed in all the profiles. The total nitrogen (TN) contents vary from 0.1% to 0.02%. The highest values occur in the surface horizons, where a sharp decrease is then observed with depth. The C/N ratios fluctuate between 7.20 and 26.5. The P contents decrease with depth for all the Vertisol profiles, except in P_1 where a slight increase is noted for the bottom horizon. Exchangeable Ca is the most represented base (15.20-26.20 cmol(+).kg^{-1}) constituting about 60 to 70% of the sum of bases. It is followed by exchangeable Mg (6.9 to 11.60 cmol(+).kg^{-1}), K (0.52 to 2.80 cmol(+).kg^{-1}) and Na (0.40 to 1.88 cmol(+).kg^{-1}, respectively. Exchangeable Ca and Mg increase with depth, while Na and K instead decrease. The sum of exchangeable bases of all the Vertisol profiles fluctuate between 24.36 and 38.94 cmol(+).kg^{-1} and increase with depth in all the Vertisol profiles. The CEC varies from 26 to 46 cmol(+).kg^{-1} and increases with depth. The Sum of The Sum of exchangeable bases increases with depth for all the profiles. The base saturation globally ranges from 74 to 100%. The SOCS of the studied Vertisols ranges from 33.28 Mg ha^{-1} to 154.13 Mg ha^{-1}. The SOCS decrease from the surface to the middle horizons before increasing to the bottom horizon in P_1 and P_2, but in P_4, an increment in SOCS is instead noted. In P_3 and P_4, the SOCS values first increase from the surface to the middle before decreasing to the bottom. The SOCS of P_5 evolves in a jig-saw trend; it decreases from the surface to the middle, increases with depth before finally decreasing towards the bottom. The TSOCS of individual horizons vary from 210.17 to 359.94 Mgha^{-1}, highest in P_1 and lowest in P_3.

Table 6. Physico-chemical characteristics of the Basin Basin Vertisols of North Cameroon

Horizon (Depth)	pH-H_2O	pH-kCl	ΔpH	OC	TN	C/N ratio	Available Phosphorus	Exchangeable bases				Sum of bases	CEC	Base saturation	SOCSh	TSOCS
								Ca	Mg	Na	K					
				(%)	(%)		(mg.kg^{-1})	(cmol(+).kg^{-1})						%	Mg.ha^{-1}	
Garoua(P_1)																
A_1(0-30 cm)	6.2	5.3	0.9	2.62	0.10	26.20	75.53	16.11	7.11	1.78	0.98	26.00	35.00	74.30	139.05	
B_1(30-100 cm)	6.6	5.3	1.3	0.36	0.02	18.00	13.91	18.58	8.98	1.03	0.40	29.00	37.00	78.40	52.92	359.94
B_{21} (100-150 cm)	6.0	4.8	1.2	0.48	0.02	24.00	10.87	24.15	11.60	0.52	0.52	36.81	40.00	92.02	53.57	
B_{3g} (150-250 cm)	5.6	4.8	0.8	0.52	0.02	26.00	30.87	24.40	11.60	0.59	0.59	37.14	42.00	88.43	114.40	
Poumpoumre(P_2)																
A_1(0-40 cm)	6.4	5.2	1.2	1.62	0.09	18.00	60.40	19.68	6.90	1.15	1.17	29.43	39.00	75.46	123.12	
B_1(40-110 cm)	6.4	5.3	1.07	0.58	0.03	19.33	16.80	21.50	9.17	0.78	0.70	32.15	42.00	76.54	85.26	301.57
B_{21} (110 – 210 cm)	6.6	5.6	0.99	0.41	0.02	20.50	12.60	26.20	9.84	0.79	0.54	36.37	46.00	79.06	93.19	
Bounguel(P_3)																
A_1(0-60 cm)	6.5	5.4	1.1	1.02	0.10	10.20	39.53	15.20	06.90	1.26	1.99	24.36	26.00	93.70	54.32	
B_1(60-150cm)	6.5	5.7	0.80	0.38	0.03	13.00	18.31	15.27	07.51	1.16	0.56	24.50	28.10	87.18	89.69	210.17
B_{21} (150-230 cm)	7.2	6.20	1.00	0.51	0.04	22.00	13.12	22.05	08.23	1.17	0.59	32.04	34.00	94.23	66.16	
Badoudi(P_4)																
A_1(0-30 cm)	6.8	6.0	0.8	1.26	0.11	11.45	81.20	22.03	9.10	1.76	0.91	32.80	33.10	99.01	66.76	
B_1(30-60 cm)	6.8	5.9	1.1	0.98	0.09	11.00	38.00	22.76	11.60	1.72	0.72	34.80	35.40	98.33	154.13	
B_{21} (60-120 cm)	7.1	5.9	1.2	0.36	0.05	07.20	22.10	23.51	9.60	1.88	0.80	35.15	37.06	95.00	39.60	293.78
B_{3g} (120-215 cm)	7.3	6.2	1.1	0.26	0.02	13.00	12.23	23.98	9.89	1.78	1.26	37.91	39.00	97.21	33.28	
Karewa(P_5)																
A_1(0-20 cm)	6.5	5.6	0.90	1.02	0.04	25.50	44.32	19.02	9.50	0.40	1.90	30.82	29.00	94.10	40.07	
B_1(20-80 cm)	7.0	6.2	0.80	0.7	0.04	17.5	19.60	18.98	11.02	0.70	2.40	33.12	32.30	97.60	34.44	247.92
B_{21} (80-140 cm)	7.4	6.2	1.00	0.51	0.02	25.5	07.10	24.24	10.92	0.98	2.80	38.94	35.92	92.22	104.66	
B3g (140-200 cm)	7.4	6.4	0.80	0.53	0.02	26.5	2.36	25.85	10.01	0.91	1.47	38.24	38.54	100	68.75	

SOCSh: soil organic carbon stocks of horizon; TSOCS: soil organic carbon stocks of profile.

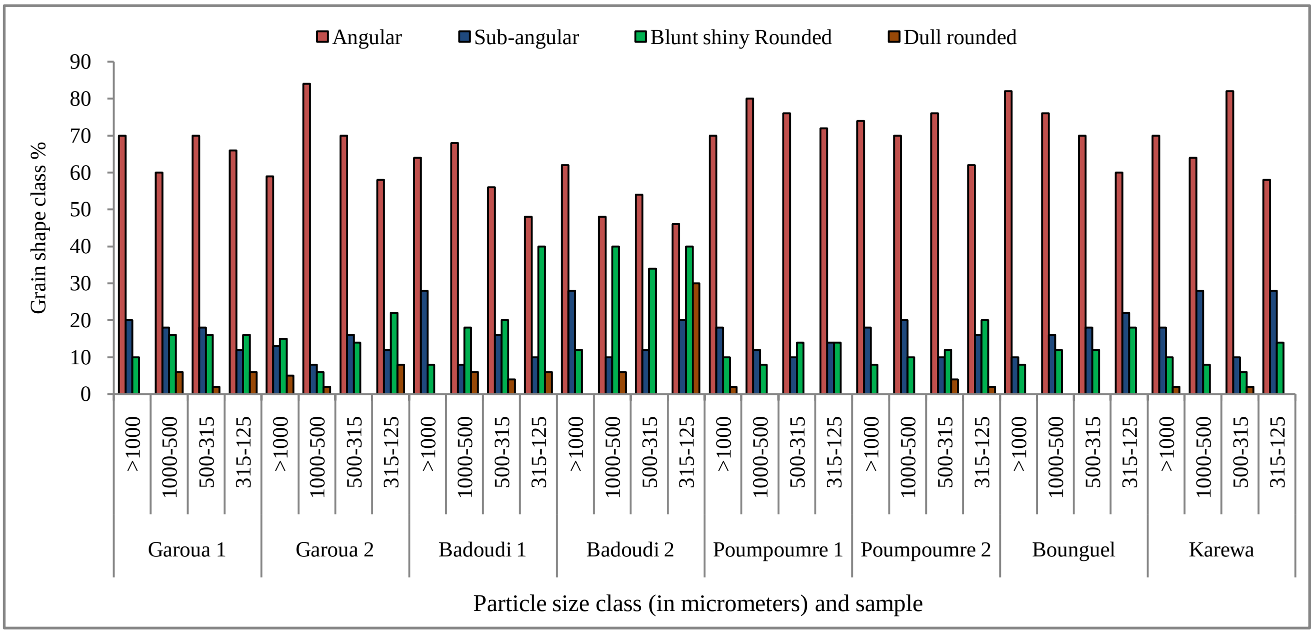

Figure 7. Proportions of grain shapes in the studied Vertisol samples for different localities in the Benue Basin of North Cameroon

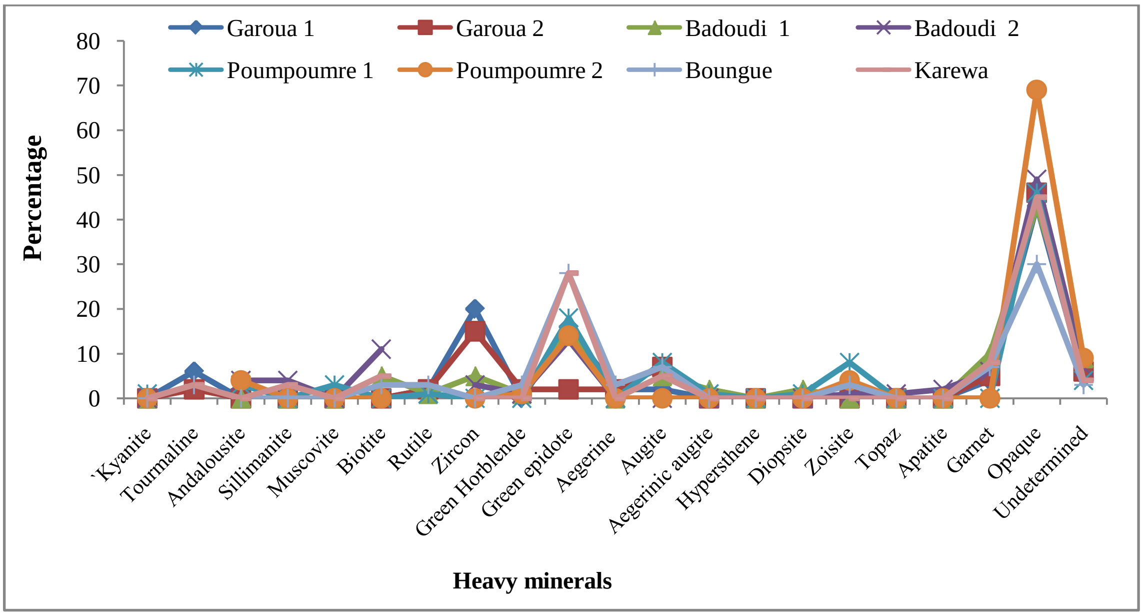

Figure 8. Composition and distribution of heavy minerals in the different Vertisol profiles

4.4. Quartz Morphoscopy and Characteristics of Heavy Mineral of the Vertisols

The quartz morphoscopy reveals the occurrence of four types of grains: angular, sub-angular, blunt shiny rounded and dull rounded grains (Figure 7). The angular grains are the most represented (48-82%) followed by the sub-angular grains (8-28%), the blunt shiny rounded grains (6-30%) and the dull rounded grains (0-30%). The general average for all samples is 66% angular grains, 16% sub-angular, 15% blunt shiny rounded and 3% dull rounded grains. Three main classes of heavy minerals are present in the Vertisols: metamorphic, magmatic and mixed minerals. The metamorphic minerals are andalusite, sillimanite, kyanite, diopside, zoisite, garnet and green epidote. Green epidote (pistachite) and zoisite (colourless epidote) indicate mild metamorphic conditions. Magmatic minerals include those that are more indicative of volcanic conditions (augite, aegerine and aegerinic augite) meanwhile tourmaline is an essential mineral of plutonic rocks. The mixed minerals include rutile, zircon, hypersthene, biotite and muscovite (Figure 8). The heavy mineral composition is homogeneous in all the sites except for green epidote, green hornblende and opaque minerals which show some variability from one site to another.

5. Discussion

5.1. Distinctiveness of the Benue Basin Vertisols in North Cameroon

Smectite is the most abundant clay mineral in the studied Vertisols, associated with small kaolinite and illite. Smectite occurs as the lone clay mineral in the some Indian Vertisols [3]. Smectite and accessory kaolinite occur in the Gezira and Fung plains (Sudan). The Vertisols in South Kenya and the West Lake Region are rich in smectite, with small kaolinite, but in the Lubiri Mbuga Vertisols in Tanzania, illite is dominant over smectite [37]. These secondary minerals, notably smectite and kaolinite might not have been formed during the present dry climate (post-depositional period) but during more humid conditions probably in the Quaternary [38]. This is because kaolinite formation requires a humid tropical climate while formation of huge amount of smectite is not feasible under such present dry climate [3]. Smectite is solely responsible for the vertic properties of Vertisols and seems to be the exclusive parent material of Vertisols [39].

In the Benue Vertisols, Silicon, aluminium, iron and titanium show a stronger concentration in all the profiles compared to the four exchangeable basic cations. This situation is common in all Vertisols and depits a strong bisiallitisation process [40]. In effect, bisiallitisation proceeds by complete accumulation of alumina and silica and partial accumulation of basic cations; their recombination under semi-arid climate and low topographic position permits the synthesis and preservation of smectite [28]. The abundance of K_2O in the Vertisols is consistent with the presence of illite identified by X-ray diffraction [41]. Positive correlation between bases and aluminium suggests that they are linked together in the clay minerals or hosted in detrital minerals during weathering in the river Basin and not significantly affected by leaching processes [42]. Negative correlation between silica and bases as well as positive correlation between bases, silicon and weathering indices could imply a relative depletion of those elements with increasing weathering intensity. A positive correlation between aluminium and phosphorus could imply that both elements are associated in the clays. Also, aluminium and titanium are positively correlated while silicon and titanium show a significant negative correlation suggesting a higher mobility of silicon relative to aluminium. A negative correlation between Mn and Fe (r=-14) suggests that original alluvial sediments were deposited under reducing conditions meanwhile enhanced sediments chemical cycling probably led to goethite precipitation [43].

Physically, although slight increase in clay content with depth is often credited to clay inheritance from parent material, clay translocation can also be assumed [3,44].

The high clay content of the Vertisols is related to the semi-arid climate, the low leaching potential of the area due to the flat topography and a clay rich alluvial parent material [17]. Desiccation cracks and slickensides are present in North Cameroon, but gilgai microrelief is absent, although reported in some Chad Basin Vertisols [9]. Gilgai is not a diagnostic feature of Vertisols [4,41,45]. The description and formation model of Gilgai microrelief is reported in [39,45]. Grunwald [4] justifies the absence of gilgai in some Vertisols due to plough action of man while [4] attributes the absence of gilgai in some North Cameroon Vertisols to erosion caused by past climatic changes.

Chemically, the studied Vertisols show a neutral to slightly acidic pH, typical of most alluvial Vertisols in the Tropics [41]. The slight increase in pH with depth suggests proximity to the parent material [47]. Some Vertisols with pH values close to 9 have been reported and attributed to the presence of free limestone in the profile [44]. The available phosphorus is globally moderate to high [48], except for some subsurface horizons where values are low. Such trends of phosphorus are similar to those of some Ethiopian Vertisols [49]. The available phosphorus reserves of the studied Vertisols exceed those of more than 70% of world Vertisols. Basic cations favour the synthesis of colloidal compounds whose interaction with humic compounds leads to its flocculation and aggregation, and subsequent stabilization [53]. This could partly justify the highly matured and stabilized organic matter in the Vertisols responsible for their dark colour.

The levels of nitrogen in the Vertisols are low and might be attributed to poor drainage [44]. The high C/N ratios indicate slow decomposition and low mobilization rate of organic matter [50]. The base saturation of the studied Vertisols is very high according to [48]. Such high values reveal extremely high fertility levels as reported in all Vertisols [51]. Together with a high CEC, the high base saturation is synonymous to a high reserve of plant nutrients [49]. The high CEC is attributed to smectite which has a large specific surface area and layer charge [14]. The SOCS varies irregularly with depth in all profiles, as already reported in [9,47]. Climate and parent material are important factors determining the quantity and distribution of SOCS in Vertisol profiles [52]. The high smectite affinity for OM helps to increase the SOCS stabilizing organic compounds.

5.2. Provenance and Sedimentary Processes

5.2.1. Source Lithotype and Influence of Regional Geology

The heavy minerals present in the Vertisols are mainly metamorphic (kyanite, sillimanite and andalusite) and plutonic (augite, aegerinic augite and aegerine) in nature, as well as a typical volcanic mineral (tourmaline) suggesting that the alluvial parent material might have been formed from the weathering and erosion of plutonic, volcanic and metamorphic rocks from the adjacent landscapes. This agrees with an Al_2O_3/TiO_2 ratio ranging of 8.72-30.40 in the studied Vertisols which suggests an origin from felsic rocks and subordinate intermediate igneous rocks. Theoretically, the Al_2O_3/TiO_2 ratio is a useful parameter to determine the source lithotype OF sediments [54]. This ratio is generally greater than 21 in sediments derived from felsic source rock, 8 to 21 in Sediments from intermediate igneous rocks and less than 8 in sediments formed from mafic source rocks. Herron [55] proposed possible sediment source using the Fe_2O_3/K_2O versus SiO_2/Al_2O_3 binary plot. The Fe_2O_3/K_2O ratio is an index of stability of ferromagnesian minerals while SiO_2/Al_2O_3 reflects the dominance of quartz or clay or feldspars. Thus, the Log (Fe_2O_3/K_2O) versus log (SiO_2/Al_2O_3) binary diagram (Figure 9) reveals that the Vertisols plot mainly in the fields of shales and wacke (one sample in the litharenite field), possible sediment sources, consistent with an aluminous siliceous composition and a moderate to high weathering intensity. The Vertisols of the Benue Trough are dominated by clay minerals suggesting that they are highly influenced by the regional geology of the area. Furthermore, the Al_2O_3/Fe_2O_3 ratios>1 and aluminum proportion >10 wt% in the studied Vertisols advocates that the protolith of the alluvial deposits are aluminum enriched [56]. The rich aluminum and silicon composition of the Vertisols possibly implies that they are genetically linked to the regional geological setting of the Benue trough in North Cameroon.

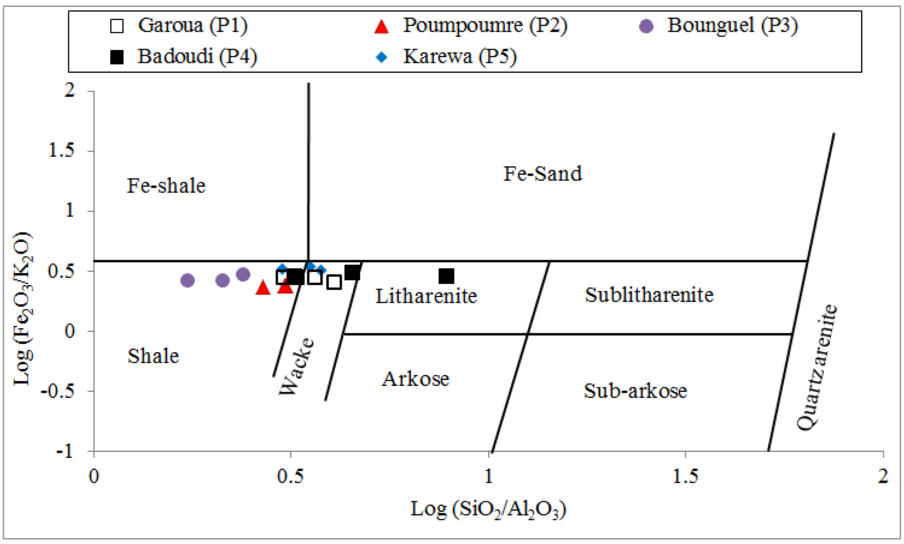

Figure 9. Plot of the studied Vertisols on Herron's diagram [55]

5.2.2. Tectonic Setting

The Vertisol samples plotted in the Active Continental Margin field [34], suggesting a distension tectonic phase probably attributed to the opening of the Southern Atlantic Ocean. This could imply that although the Vertisols are quite young, formed from recent alluvium, their protolith might have come mainly from the weathering of very old geological formations of cretaceous age and Precambrian formations [22,57]. The active continental margins are subduction-related basins, continental basins and pull-apart basins associated with strike-slip fault zones [22]. In detail, the Na_2O-CaO-K_2O discriminant plot of Toulkeridis [34] reveals that the studied Vertisols belong to an Active Continental margin and continental island arc. This aspect is understood as the studied area lies on two intra-continental cretaceous sedimentary basins (Benue and Garoua basins) and is close to numerous other intra-continental sedimentary basins (Babouri-Figuil, Mayo Oulo Lere, Koum, Hamakoussou, etc).

This tectonic activity is probably related to the formation of the Benue Trough [57,58]. The discriminant function-based multidimensional tectonic diagram of [59] indicates an arc to minor collisional setting. Based on the context of sediment deposition, it is documented [57] that Cameroonian sedimentary basins are formed by rifting; one would have expected all the samples to instead fall in the "rift" domain but this is not the case, probably suggesting that the parent materials of the Vertisols (protolithe) might have come from the Pan-African basement of the Central African Fold belt. This basement was affected by subsidence in the Lower Cretaceous, probably the Neocomian, giving high reliefs whose erosion led to the sediments transport and deposition in river floodplains [22]. These sediments then underwent pedogenesis and structural reorganisation to form Vertisols. These Vertisols have recorded the characteristics of their parent materials enabling to reconstitute the geological history of the area

5.2.3. Weathering Indices and Palaeoclimatic Implications

The Ruxton index (SiO_2/Al_2O_3 ratio) of the Vertisols ranges from 2.27 to 3.55, suggesting moderate to intense weathering and a dominant bisiallitisation process [28]. The SiO_2/Al_2O_3 ratio of pure smectite generally varies between 2.8 and 3.31, whereas that of kaolinite is about 1.18 [54]. SiO_2/Al_2O_3 ratios >3 indicate the predominance of smectite while ratios between 2 and 3 indicate mixture of smectite, illite and/or kaolinite [60].

The K_2O/Al_2O_3 ratio has been used to indicate the clay mineralogy in sediments [54]. In sediments enriched in illite, K_2O/Al_2O_3 ratios generally range from 0.2 to 0.3 whereas enrichment in kaolinite, smectite and/or vermiculite is suggested if this ratio is close to 0 [61]. In the studied Vertisol, K_2O/Al_2O_3 values range from 0.05 to 0.14 (<0.2) suggesting high Smectite, Kaolinite and/or vermiculite. The Kaolinite-to-illite ratios (1.83-7.40) of the studied Vertisols confirm the dominance of kaolinite over illite. Also, the smectite-to-kaolinite ratios vary from 2.28 to 4.31 confirming the dominance of smectite over kaolinite. The CIA and PIA indicate the degree of weathering in sediment source areas, and thus, reflect their tectonic setting and prevailing palaeoclimatic conditions [62]. High CIA values (76-100) indicate intense chemical weathering, whereas the moderate values (76-50) indicate moderate weathering and low values (CIA≤50) reflect unweathered source areas [63]. The CIA values of the studied Vertisols fall within the range of moderately to intensely weathered materials [29]. Such values can be attributed either to intense recycling in humid and/or semiarid climatic conditions [54]. The SiO_2 versus Al_2O_3+K_2O+Na_2O diagram (Figure 10) of Suttner and Sutra [61] indicates a semi-arid climate during pedogenesis. The weathering and pedogenesis probably occurred during an active recycling context in a more humid post-depositional period of the alluvial parent material [64]. In effect, numerous phases of climate variations have been reported in the Quaternary (2.8 Ma) of North Cameroon, alternating between dry and wet periods [65]. The last wet period is the African Humid Period (15 to 5.5 ka) [65], with the climate optimum occurring at the beginning of the Holocene (11.7 ka), referred to as the Green Sahara [8] and since the end of the African Humid Period (5.5 ka), climatic conditions have become drier.

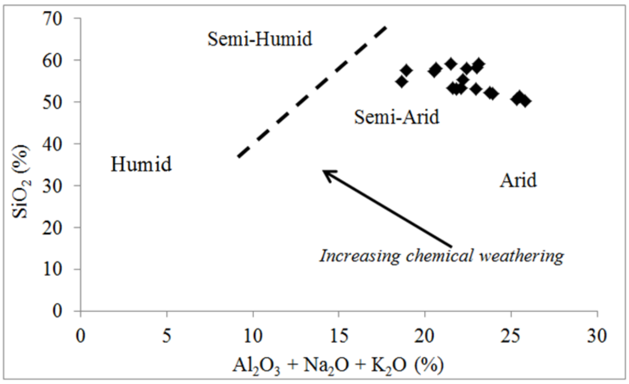

Figure 10. SiO_2-(Al_2O_3+Na_2O+K_2O) binary plot of the Benue floodplain Vertisols based on the Suttner and Sutra [61]

5.2.4. Sedimentary Processes: Detrital Transportation, Sorting and Sediment Cycling

The low levels of Fe in the Vertisols (<10%) and similar CIA and PIA values at different sites suggest that the alluvial material underwent mostly mechanical transport from the uplands to the river basins. The abundance of angular shaped grains (>70%) in the sand sized fraction indicates that the source of the alluvial parent material is proximal probably due to the gentle slope of the Benue plain that gives little kinetic energy hindering long fluvial transport distance. The regular distribution of heavy minerals and grain shape classes in the river Basin indicates low effect of transportation on sorting leading to poor sorting. The chemical composition of alluvium could have been influenced by hydraulic sorting; according to [65], hydraulic sorting fractionates clay minerals from coarse silt and sand containing quartz and feldspars associated with heavy minerals. In this semi-arid fluvial environment, most of the alluvial material originates from transportation by tributaries and material brought in by erosion of the nearby landscapes during rainfall. The blunt shiny round grains in the materials, although in a low proportion, justifies wind transport agent as this zone is subjected to prolong dry season within the year. The similar chemical composition of the Vertisols in the different sites suggests parallel weathering and transport rates of materials and comparable topological variations of the basin.

The K_2O/Na_2O ratio is useful in deducing recycling of sediments [66]. The K_2O/Na_2O ratios of the Benue Basin Vertisols range from 0.83 to 3.34 suggesting a low to high amount of sediment recycling or chemical maturity. However, as the mean K_2O/Na_2O ratio stands at 2.10>1 and only two horizons out of 18 show ratios less than 1, it is suggested that the Benue Vertisols generally show a high chemical maturity.

5.3. Classification of Vertisols of the Benue Basin of North Cameroon

In the Vertisols of the Benue Basin, there is no lithic or paralithic contact, petrocalcic horizon, or duripan within 50 cm depth from the surface. The clay content within 50 cm depth is above 30% after soil mixing to 18 cm depth. The presence of open desiccation cracks within 50 cm depth is typical of all Vertisols. They show slickensides in the middle part of the profile with long axis tilted at an angle to the horizontal. These Vertisols are subjected to drought for more than 90 cumulative days but less than 180 days, typical of Ustic moisture regime. This enables those soils to be referred to the class of Usterts Suborder. They are exposed to a mean annual temperature of more than 22°C, typical of the Clayey Isohyperthermic family and to the class of Ustic Haplusterts clayey isohyperthermic. Due to their occurrence in floodplain tidal marshes, they are classified as Alluvial Vertisols according USDA soil taxonomy [67]. They are under aquic conditions at or near the surface for extended periods within the year, but dry for periods long enough in normal years to enable opening of cracks and thus enabling them to be referred to as Aquerts Vertisols [68]. The presence of glei horizons due to the presence of a perched water table enables to classify them as Epiaquerts Vertisols. These Vertisols show a value of ≤3 and a chroma of ≤2 in the Munsell Soil Colour Chart enabling to classify them as Pellic Vertisols. They have glei horizons (Gleyic), high base saturation (>>50%) between 20 and 100 cm of the mineral surface horizon (hypereutric), a water saturation at least for a certain period of the year (Stagnic) and clay content greater than 30% within 30 to 100 cm depth (Clayic). *These Vertisols are thus* classified as Gleyic Stagnic Vertisols (Pellic, Hypereutric, Clayic) according to WRB [69].

5.4. Environmental Conditions and Management of the Vertisols

The environmental conditions of the studied area in North Cameroon and their consequences on the nature, classification and management of Vertisols are summarised in Table 7. The major pedogenetic factors (tropical climate with long dry season, alluvial parent material and low topographic position) favour the formation of a peculiar morphology as well as a typical geochemistry and mineralogy. The high chemical maturity and moderate to high weathering intensity are related to the environmental conditions of deposition of the alluvial parent material. This alluvium has undergone short fluvial transport distance from the original source rock probably felsic rocks and subordinate intermediate rocks.

Table 7. Summary of environmental conditions and their consequences on the nature of Vertisols in the Benue Basin of North Cameroon

Soil pedogenetic conditions, characteristics, geochemical parameters and classification			Description
Pedogenetic factors	Climate		Tropical climate with a well-marked long dry season
	Parent rock		Alluvium enriched in basic cations,
	Topography	Typical landform	Alluvial terrace, Ancient floodplain
		Slope	None
		External drainage	slow
		Erosion	Mild
Soil morphological features	Gilgai microrelief		Absent
	Desiccation cracks		present
	Slickensides		Present
	Horizon differentiation		Mild based mainly on structural organisation and colour
	colour		Grey to very dark grey (low chroma)
	Texture		Clay to heavy clayey
Mineralogical and geochemical characteristics	Clay mineralogy		Smectite dominant, with accessory kaolinite and illite
	Geochemistry		Accumulation of silica and alumina (bisiallitisation)
	Chemical characteristics		High CEC, high base saturation (S/T>80%)
	Heavy minerals		Metamorphic (kyanite, sillimanite, andalusite), plutonic (tourmaline) and volcanic (augite, aegerinic augite) minerals
Provenance	Chemical maturity		High
	Weathering intensity		Moderate to high
	Source lithotype		Al_2O_3/TiO_2 ratio of 8.72 to 30.40 suggest origin from felsic rocks and subordinate intermediate igneous rocks
Soil classification	USDA Soil Taxonomy [60]		Ustic Haplusterts Clayey Isohyperthermic
	WRB [70]		Gleyic Stagnic Vertisols (Pellic, Hypereutric, Clayic)
Management	-		Moisture control, dry season farming, irrigation, water-harvesting, raised beds, etc

USDA Soil Taxonomy: United States Department of Agriculture Soil Taxonomy; WRB: World reference Base for Soil Resources.

The classification of those Vertisols as Ustic Haplusterts Clayey Isohyperthermic [69] and as Gleyic Stagnic Vertisols (Pellic, Hypereutric, Clayic) [70] is a consequence of their pedogenic conditions and resulting characteristics. Thus, management strategies for agriculture and other engineering uses ought to be directed primarily at moisture control. Vertisols occupy more than 1,200,000 hectares in North Cameroon representing a major resource for large scale crop cultivation [16]. They are used for the cultivation of counter-season sorghum and irrigated rice but adapted management is a precondition for sustainable production. Due to the unfavorable physical properties of these soils like dry season cracking, raining season ponding, most farmers in North Cameroon simply do not plant on Vertisols during the rainy season [71]. Also, most Vertisols have simply been reserved for grazing, charcoal burning, forest reserves and small post-rainy season farming [71]. No-till is an economical practice in North Cameroon.

6. Conclusion

In this study, the geochemical properties of Vertisols developed on alluvial sediments in the Benue basin were used to constrain their provenance, source area-weathering, sedimentary processes, tectonic setting, taxonomic level and management strategies. The main results revealed that original parent material of the alluvial parent material of the Vertisols is formed in an Active Continental Margin probably from the Pan-African basement of the Central African Fold belt. These source rocks of the sediments were probably metamorphic, plutonic and volcanic as suggested by the nature of the heavy minerals in the Vertisols typical of these rocks. The Al_2O_3/TiO_2 ratio (8.72-30.40) suggests mainly felsic rocks and subordinate intermediate igneous rocks. These geological facts are recorded in the Vertisols and enable to reconstitute the geological history of the area. The major weathering process in the Vertisol is bisiallitisation as revealed by the abundance of 2/1 clays, mainly smectite, suggesting that weathering might have occurred during a more humid climate in the past. Precisely, the chemical index of alteration, plagioclase index of alteration and Ruxton index are high and suggest a warm and humid climate during moderate to intense chemical weathering probably prevailing during a more humid pre-depositional period. The short fluvial transport distance and poor sorting of the Vertisols, as revealed by the predominance of angular quartz grains, portray low fluvial energy imposed by a flat topography in the studied area. The classification of the Vertisols as Gleyic Vertisols and Fluvic Vertisols (World Reference Base for Soil Resources), and as Ustic Haplusterts Clayey Isohyperthermic (United States Department of Agriculture) agrees with classification of true Vertisols. The particular physical characteristics of the Vertisols caused by their shrink-swell behaviour enable to recommend management strategies for agricultural and other engineering purposes that are mainly tilted primarily at moisture control.

Conflict of Interest

The authors did not declare any conflict of interests.

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