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Mineralogical, Geochemical and Physico-Chemical Characterization of Clay Raw Materials from Three Clay Deposits in Northern Cameroon

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Abstract

The characterization of clay raw materials of three clay deposits from Northern Cameroon was investigated. The three deposits, located in Gaschiga, Sekandé and Boulgou, are locally used as building materials, but no data are available on these materials and they are relatively unknown. Mineralogical, geochemical and physico-chemical characteristics were studied, using X-ray diffraction, X-ray fluorescence and physico-chemical analyses. Mineralogically, quartz was the most abundant mineral in the studied raw materials. It is associated to abundant quantity of smectite, kaolinite and K-feldspars, and slightly abundant to traces of hematite and amphibole. Geochemically, those clayey soils are more siliceous (SiO_2, 51% - 59%) with significant amount of aluminum (Al_2O_3, 15% - 19%) followed by iron oxides (Fe_2O_3, 3% - 10%). Other oxides (K_2O, MgO, TiO_2, Na_2O, MnO, CaO and P_2O_5) are in relatively lower proportion. High level of silica content explains the sandy nature of these clays. The results of granulometric analysis show that the studied raw material contain sand (39% - 68%) as major grain size followed by clay particles (17% - 38%), silt (1% - 36%) and gravels (0% - 16%). The studied clayey soils were moderately plastic, with plasticity index values ranging from 13% to 30%, and are also characterized by very high liquidity limits of 34% - 63%.

Keywords

Clay Material, Characterization, Mineralogical, Physico-Chemical, North-Cameroon

1. Introduction

Clay is a widely distributed abundant mineral resource of major industrial importance for an enormous variety of uses (Ampian, 1985; Reeves et al., 2006; Murray, 2007). According to Velde (1983) clay is applied both to materials having a particle size of less than 2 μm and to the family of minerals that has similar chemical compositions and common crystal structural characteristics. This material also has the power to be shaped, to shrink, to harden after drying and to consolidate after firing, which allows the formation of a vitreous phase more or less important (Melo et al., 2003; Kamseu et al., 2007; Pialy, 2009). They have varying chemical composition depending on both the physical and chemical changes in the environment where clay deposits are found (Salawudeen et al., 2010). In the context of sustainable development and technological innovation relative to the field of futuristic research, the study of clay and its properties for various applications appears as an imperative. Clay deposits have been identified in all regions in Cameroon (Sieffermann, 1959; Nkoumbou et al., 2001; Mefire et al., 2015; 2018; Basga et al., 2018; Nchare et al., 2018; Nzeukou et al., 2021) though with differing properties probably owing to geological differences. It is the reason why many houses in cities and villages are built using these materials due to the social and economic factors. In the North Cameroon for example, clay materials are mainly used for the manufacture of different pottery items and building materials such as bricks (Djenabou et al., 2015; Temga et al., 2015; 2018; Tsozué et al., 2017; Yanné et al., 2018; Nguiamba et al., 2019; Nzeukou et al., 2021; Yaboki et al., 2021). These activities, practiced by craftsmen during the dry season, bring them finances to meet their needs. While the consumption of these products tends to become widespread, their production remains very unsustainable in some developing countries. This situation can be explained by the virtual absence of a real industrial fabric and a poor estimation of the local resources potential. Therefore, the evaluation of this natural resource has an important effect on the economic development of countries. The exploration of new clay deposits in developing countries such as Cameroon could significantly contribute to socio-economic development, as this helps also identifying the original materials. Many factors intervene in all industrial applications of clay material. They include their structure, composition and physical properties. This paper aims to characterize the clay raw materials collected from three clay deposits in the northern part of the Cameroon. In detail, it will be to characterize the clay raw material on the mineralogical, geochemical and physico-chemical composition view point. The results of the work will be used to improve a database to support the start-up of industrial projects for local clay materials.

2. Materials and Methods

2.1. Study Area

The study area is located at the center of the Benue valley in North Cameroon, between latitudes 10˚10' and 9˚30''N and longitudes 13˚15' and 13˚46'E (**Figure**

1). The study was undertaken in three localities, Gaschiga, Sekandé and Boulgou (Table 1). They were chosen mainly for their traditional used as building materials. The climate is characterized by a Sudanian climate, with two contrasted seasons: a humid one from May to October and a dry one from November to April. Total yearly precipitations vary between 900 and 1500 mm and mean annual temperature is 28˚C. The general landscape is composed of two geomorphological units, extensive plain whose monotony is interrupted here and there

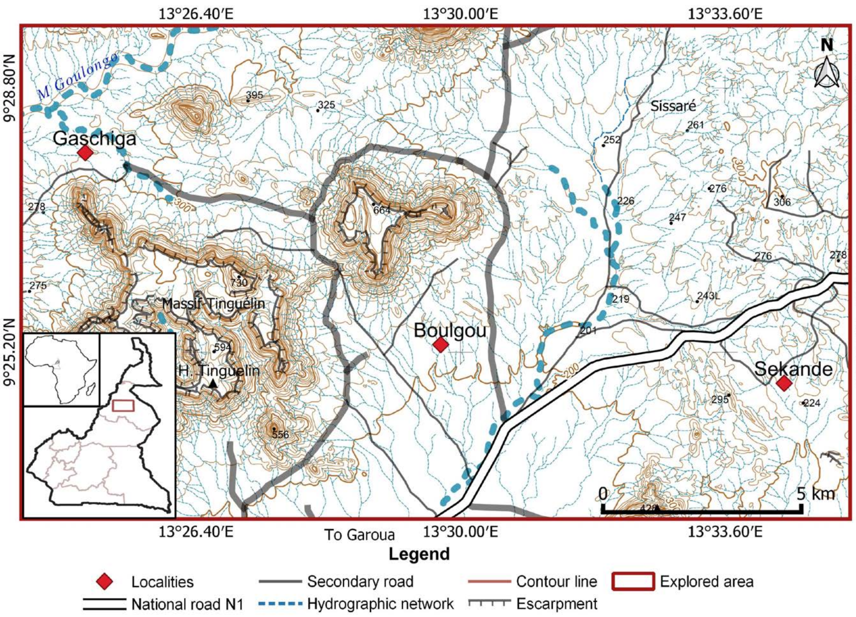

Figure 1. Location of the study area.

Table 1. Geographical coordinates of the sampling points.

N˚	Profile	Sampling code	Geographic coordinates	Explored site
1	GA1	GA1C2	09˚25'41.5"N; 13˚24'00.6"E and 271 m	
2	GA1	GA2C2	09˚26'47.4"N; 13˚23'26.3"E and 239 m	**Gaschiga**
3	GA1	GA3C2	09˚26'20.6"N; 13˚23'36.6"E and 256 m	
4	SK1	SK1C2	09˚24'57.2"N; 13˚32'02.1"E and 223 m	
5	SK1	SK1C3	09˚24'57.2"N; 13˚32'02.1"E and 223 m	
6	SK2	SK2C2	09˚24'50.9"N; 13˚32'55.6"E and 228 m	**Sekandé**
7	SK3	SK3C2	09˚24'59.7"N; 13˚31'58.8"E and 226 m	
8	SK4	SK4C3	09˚24'34.9"N; 13˚37'52.1"E and 230 m	
9	BO1	BO1C2	09˚25'37.0"N; 13˚28'25.0"E and 241 m	
10	BO2	BO2C2	09˚25'56.2"N; 13˚28'03.1"E and 259 m	
11	BO3	BO3C2	09˚24'54.3"N; 13˚28'36.4"E and 229 m	**Boulgou**
12	BO5	BO5C2	09˚24'36.5"N; 13˚28'60.1"E and 210 m	
14	//	SPmG	09˚26'06.2"N; 13˚27'12.6"E and 420 m	

by small hills or “inselbergs”. The inselbergs, 200 to 800 m a.s.l., are characterized by gentle to steep slopes. The substratum is made by Meso to Neoproterozoic gneissic basement and continental sediments (sandstones) of the Middle to Upper Cretaceous age (Ngounouno et al., 2001; 2003) (**Figure 2**). The vegetation is a seasonally flooded prairie which is strongly modified by farming activities (Letouzey, 1980). The superficial formations are mainly constituted of vertisols associated with ferruginous soils (Raunet, 2003; Tamfuh et al., 2011; 2018; Kagonbé et al., 2020a).

2.2. Sampling

Field work was carried out during the dry season and consisted of direct observations, description of environmental settings and soil survey in order to choose the position of pits. **Table 1** outlines the profile code, sampling code and their geographic coordinate. Eleven pits were dug in three localities (Gaschiga, Sekandé and Boulgou) and thirteen samples were collected: five in Sekandé (SK1C2, SK1C3, SK2C2, SK3C2 and SK4C3), three in Gaschiga (GA1C2, GA2C2 and GA3C2) and five in Boulgou (BO1C2, BO2C2; BO3C2, BO5C2 and SPmG (**Table 1**). The samples were selected on the basis of their color and homogeneity. About 30 kg of each sample were collected and placed in polythene bags, labeled and sent to the laboratory for analyses.

2.3. Analytical Techniques

Mineralogical and geochemical analyses were done at the Research Unit Clay, Geochemistry and Sedimentary Environments (AGEs) of the University of Liege in Belgium. X-ray diffraction patterns were obtained with a diffractometer (Bruker Advance 8) equipped with Ni filtered CuKα radiation, with automatic slit and on-line computer control. The samples were scanned from 2˚ to 45˚ 2θ. Chemical analyses were obtained by atomic absorption spectroscopy. Loss on ignition (LOI) was measured from total weight after ignition at 1000˚C for 2 h.

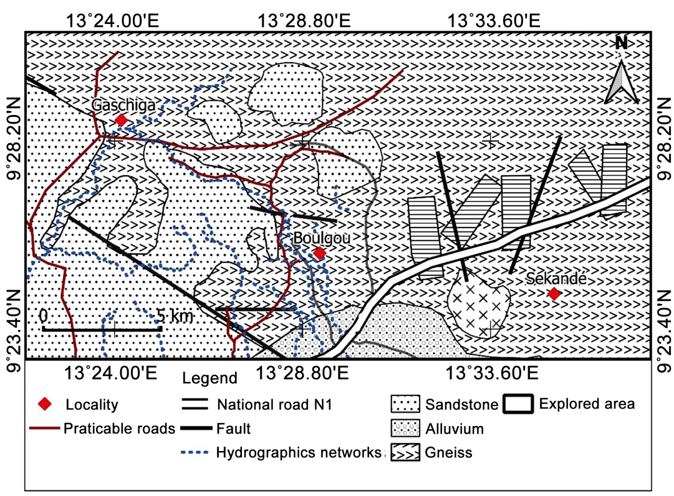

Figure 2. Geological map of the study area.

The chemical alteration index (CAI or CIA) is considered to be a good measure for the degree of weathering (Nesbitt & Young, 1982). Its calculation is based on molecular proportions: CIA = $Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O) \times 100$. In the equations, CaO^* is associated with the silicate fraction and corrected for inputs from carbonate and apatite (Ozaytekin & Uzun, 2012). Since Al is much more immobile than the alkali elements (Na^+ and K^+) and Ca^{2+}, changes in CIA reflect changes in the proportions of feldspar and the various clay minerals developed in the clay raw materials. For the semi-quantitative analysis of the samples, the relative abundance of minerals was estimated from the intensity of the main reflections. Physico-chemical properties were determined at the laboratory of Locals Material Promotion Authority (MIPROMALO) of Yaoundé in Cameroon. The grain size distribution was determined following the NF P18-560 standard by dry sieving and the P94-057 standard by sedimentation. The plasticity was measured by the Atterberg limits: plastic limit and liquid limit according to the ASTM, D 4318-10 norms. The plasticity indices were calculated after the determination of Atterberg limits (Casagrande, 1948).

3. Results

3.1. Mineralogical Composition

The results of the mineralogical analysis on disoriented powder of thirteen samples collected are illustrated in **Table 2**. They show the predominance of quartz, followed by smectite, kaolinite and K-feldspar which is present in all samples of the three localities, but in various proportions. In Gaschiga, quartz is the most

Table 2. Semi-quantitative estimation, based on X-ray diffraction, of the mineralogical composition of the Gaschiga and Sekandé samples.

Site	Samples	Quartz	Smectite	Kaolinite	K-feldspar	Hematite	Amphibole
Gaschiga	GA1C2	++++	+++	+++	+++	/	/
	GA2C2	++++	+++	+++	+++	/	/
	GA3C2	+++	+++	+++	+++	/	/
Sekandé	SK1C2	+++++	+++	++	+++	/	+
	SK1C3	+++++	++	++	+++	/	++
	SK2C2	+++++	+++	++	+++	/	++
	SK3C2	+++++	++	++	+++	/	++
	SK4C2	+++++	++	++	+++	/	/
Boulgou	BO1C2	+++++	+++	+++	++	++	++
	BO2C2	+++++	++	+++	++	++	++
	BO3C2	+++++	++	+++	++	++	++
	BO5C2	+++++	++	+++	++	++	++
	SPmG	+++++	++	+++	++	/	/

/: none; +: traces; ++: very slightly abundant; +++: slightly abundant; ++++: abundant; +++++: very abundant.

abundant mineral followed in the same proportion by smectite, kaolinite and K-feldspar. In Sekandé, quartz is also the main mineral, but highly expressed here than in Gaschiga. It is followed by smectite and kaolinite which quantities on contrary are lower. K-feldspar remains in the same proportion as in Gaschiga. In Boulgou, quartz remains the most represented mineral. Contrary to the two other sites, kaolinite is the most important mineral here after quartz. It is followed by smectite and K-feldspar, which quantities are globally low compared to the two other sites. The Boulgou site stands out from other sites by the presence of hematite, which quantities are similar to those of smectite. Also, amphibole, another primary mineral, is present in the study area. It is observed only in Sekandé and Boulgou.

3.2. Geochemical Composition

The geochemical composition of the clay samples is illustrated in **Table 3**. The results show that the most abundant oxides are silica (SiO_2) followed by alumina (Al_2O_3), iron (Fe_2O_3) and potassium (K_2O). SiO_2 ranged from 53% to 59% in Gaschiga, 50% to 59% in Sekandé and 51% to 58% in Boulgou. It is followed by Al_2O_3, which quantities vary between 15% to 18% in Gaschiga, 17% to 20% in Sekandé and 15% to 18% in Boulgou. Fe_2O_3 quantities are low in Gaschiga and range between 3% to 6%. At Sekandé and Boulgou, its proportions range between 6% - 10% and 5% - 8% respectively. These three main oxides are followed by K_2O and MgO. K_2O proportions range from 1% - 3%, 0.2% - 3% and 2% - 3% in Gaschiga, Sekandé and Boulgou respectively. MgO proportions are also low, with values globally ranging between 0.98% and 2.89% in all the study sites. CaO and Na_2O proportions are also low. They range globally between 0% and 3.75% for CaO and 0.56% and 2.59% for Na_2O.The proportions of P_2O_5, TiO_2 and MnO are very low, with values below 1.68%. The loss of ignition, an important indicator of the weathering degree is high, ranging between 6% to 15%. The SiO_2/Al_2O_3 ratio was >2%, indicative of an excess of SiO_2 in the studied clays. The sum of $TiO_2 + Fe_2O_3 + CaO + MgO + Na_2O + K_2O$ is high. Its values vary between 9.91% and 20.23%. The chemical index of alteration (CIA) ranged globally between 67.20% and 87.30%, indicating that the studied clay deposits are constituted of very weathered raw material (**Table 3**). It is noted however that the most weathered material is observed in Sekandé.

3.3. Physico-Chemical Properties

Table 4 summarizes the physicochemical characteristics of the different samples. Globally, the result reveals that the particle size distribution varying slightly between different studied localities. The proportions of particles more than 2 mm in size, vary from 17% - 33% for Gaschiga, 26% - 38% for Sekandé and 20% - 32% for Boulgou. Clay fraction has the medium quantities. Silt fraction has the lowest quantities in Boulgou. They range between 1% to 8%. In Gaschiga and Sekandé their values vary from 11% to 36% and 11% to 16% respectively. Sand is

Table 3. Major elements and loss on ignition (LOI) of the studied clays.

Samples/major elements	Gaschiga			Sekandé					Boulgou			
	GA1C2	GA2C2	GA3C2	SK1C2	SK1C3	SK2C2	SK3C2	SK4C3	BO1C2	BO2C2	BO3C2	BO5C2
SiO_2	54.20	53.20	59.25	56.92	59.84	50.68	52.34	55.39	58.60	51.76	58.90	57.29
Al_2O_3	15.78	18.02	18.55	17.96	17.51	19.77	18.05	20.33	16.00	18.50	15.19	16.73
Fe_2O_3	3.46	6.02	6.10	6.92	6.27	9.16	10.07	8.10	6.13	8.54	6.83	5.66
K_2O	3.13	1.94	1.61	0.20	0.61	2.26	2.34	3.20	2.64	2.24	3.26	2.86
MgO	1.25	2.35	1.96	1.74	1.65	2.77	4.48	1.42	0.98	1.45	2.89	1.24
TiO_2	0.05	0.04	0.06	0.84	0.73	1.16	0.92	0.99	1.11	1.68	1.39	1.31
P_2O_5	0.27	0.35	0.04	0.28	0.25	0.01	0.26	0.94	0.24	0.42	0.41	0.19
CaO	0.17	0.57	1.84	1.69	1.12	1.85	0.55	0.00	2.78	3.75	1.56	2.91
Na_2O	1.85	1.40	1.74	0.97	0.82	1.14	0.56	0.99	2.27	2.57	2.59	2.18
MnO	0.26	0.41	0.06	0.05	0.05	0.07	0.07	0.78	0.08	0.09	0.13	0.08
LOI	15.87	14.99	7.53	10.27	12.00	10.86	10.09	8.48	6.97	7.44	6.42	7.94
Total	**96.29**	**99.29**	**98.74**	**97.84**	**100.85**	**99.73**	**99.73**	**100.62**	**97.78**	**98.44**	**99.57**	**98.39**
SiO_2/Al_2O_3	3.43	2.95	3.19	3.16	3.41	2.56	2.89	2.72	3.65	2.79	3.87	3.42
CIA	75.39	82.20	78.14	86.30	87.30	79.02	84.00	82.91	67.60	68.40	67.20	67.80
$TiO_2 + Fe_2O_3 + CaO + MgO + Na_2O + K_2O$	9.91	12.32	13.31	12.36	11.2	18.34	18.92	14.7	15.91	20.23	18.52	16.16

Table 4. Physico-chemical characteristics of the studied clays.

Site	Sample	Organic matter (%)	Gravel (%) Φ > 2 mm	Sand (%) 2 > Φ > 0.02 mm	Silt (%) 0.02 > Φ > 0.002 mm	Clay (%) Φ < 0.002 mm	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
Gaschiga	GA1C2	5.39	2.80	43.10	36.30	17.80	63.40	36.90	26.50
	GA2C2	3.82	7.50	45.30	17.30	29.90	60.70	30.80	29.90
	GA3C2	6.98	4.60	49.90	11.90	33.60	48.00	30.30	17.70
Sekandé	SK1C2	5.98	5.80	45.50	15.20	33.50	50.90	24.40	26.50
	SK1C3	4.57	3.01	50.00	16.20	30.70	55.70	27.00	28.70
	SK2C2	4.35	8.50	53.20	11.90	26.40	43.50	24.50	19.00
	SK3C2	6.40	8,80	39.70	15.30	36.20	60.90	32.70	28.20
	SK4C3	4.71	1.70	48.00	12.00	38.30	55.80	25.80	30.00
Boulgou	BO1C2	3.02	16.00	50.00	1.00	26.00	43.20	22.50	20.70
	BO2C2	2.31	5.00	59.00	8.00	20.00	34.10	20.30	13.80
	BO3C2	2.68	2.00	68.00	8.00	22.00	38.10	24.80	13.30
	BO5C2	2.07	0.00	59.00	5.00	36.00	36.00	18.10	18.00
	SPmG	3.45	7.00	65.93	7.00	20.43	56.50	23.50	33.10

the most important fraction. Its quantities are 43% to 50% in Gaschiga, 39% - 50% in Sekandé and 50% - 68% in Boulgou. The higher proportions are observed in Boulgou.

The gravels are slightly represented in clay raw material. Their quantities vary from 0% to 16%. Only BO1C2 presents the higher value. The presence of organic matter in a raw material is inconvenient and undesirable. Organic compounds particularly reduce the strength of a building material. They cause corrosion and softening in the material over time. Their proportions vary between 2% to 6%. The liquid limit of studied samples ranged between 36% and 63% (**Table 4**; **Figure 3**), while the plastic limit values were between 18% and 36%. The highest plastic value (LL > 63%) was observed in the GA1C2 sample. The resulting plasticity indexes ranged between 17% and 33%.

4. Discussion

The mineralogical analysis of the studied clayey materials is characterized by relatively high contents of quartz followed by smectite, kaolinite and K-feldspar, with small proportions of amphibole observed in Sekandé and Boulgou, as well as hematite only observed in Boulgou. Except the GA3C2 sample coming from Gaschiga, the proportion of quartz is very abundant in all localities. Smectite clay mineral was responsible for the extensive swelling and shrinking upon drying and wetting, the major characteristic of all vertisols (Duchaufour, 1977; Soil Survey Staff, 1999; FAO, 2006; Aydinalp, 2010). The high smectite content in the studied clay material was related to the low landscape positions, a strongly contrasted climate and the presence of a clay-rich alluvial parent material (Boulvert, 1968; Bocquier, 1973; Gavaud, 1975; Duchaufour, 1977). The predominance of smectite suggests that the chemical process acting in the study area is bisiallitisation (Pédro, 1966; Temga et al., 2015). All the studied clay bodies are rich in quartz and kaolinite which suggest felsic sources. Kaolinite is formed by the

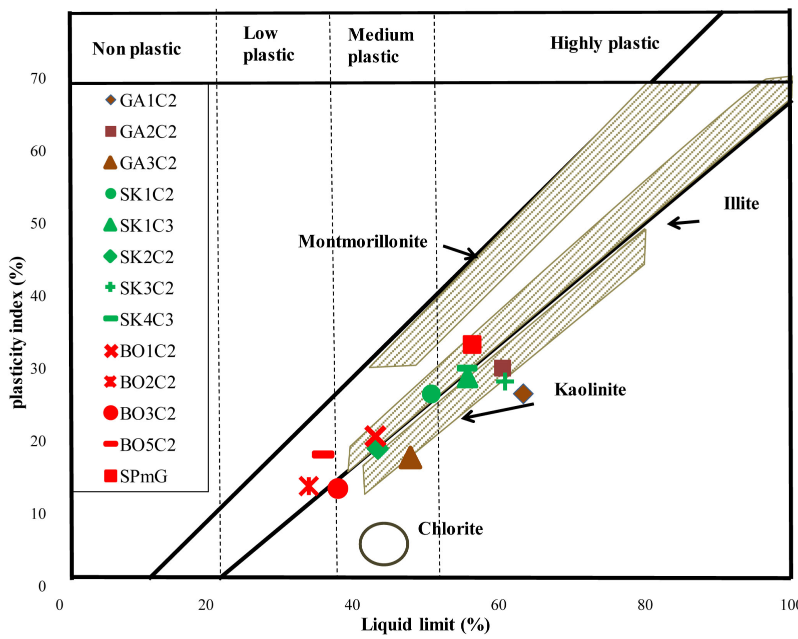

Figure 3. Casagrand's plasticity chart (Holtz & Kovacs, 1981) showing representative clay material samples.

decomposition of orthoclase feldspar in granite (Nzeukou et al., 2021; Yaboki et al., 2021). The existence of hematite in the Boulgou is tributary to the significant iron oxide contents Fe_2O_3, is in line with the presence of amphibole. The presence of kaolinite suggests that monosiallitisation is a crystallochemical processes acting in the study area towards bisiallitisation (Pédro, 1966).

The studied clayey materials are characterized by relatively high contents of SiO_2 followed by Al_2O_3 and Fe_2O_3. However, it also contains some minor elements such as potassium, sodium and titanium oxides. The SiO_2 content should be associated with the presence of quartz particles: a highest value for all sample refers to the higher sand fraction in particle size distribution analysis and higher quartz content in mineral composition. Alumina (Al_2O_3) reflects the presence of aluminosilicates. Iron (Fe_2O_3) is related to the presence of hematite while potassium (K_2O) is binded to the presence k-feldspars (Nzeukou et al., 2021). The high SiO_2/Al_2O_3 ratio > 2 wt%, suggests the presence of free-form of silica and 2:1 clay mineral types (Crook, 1974; Temga et al., 2015) and indicates high chemical maturity of the investigated samples (Maignien, 1958; Tsozué et al., 2017; Temga et al., 2015). A representation in the triangular diagram SiO_2-Al_2O_3-Fe_2O_3 showed that all sample were localized on SiO_2-Al_2O_3 axis (**Figure 4**), toward SiO_2 pole in line with high SiO_2/Al_2O_3 ratio. This is indicative of an excess of SiO_2 in the studied soils and confirmed the presence of quartz and 2:1 phyllosilicates of montmorillonite type (Tsozué et al., 2017).

The suitability of clays for different industrial applications is based on their particle size distribution. Particle size distribution of clay plays an essential role in defining the properties of suspensions (plasticity and viscosity) and green pastes during drying and firing (Rivi & Ries, 1997; Basga et al., 2018). Grain-size distribution also affects the microstructure and the mechanical properties of fired materials (Ngun et al., 2011; Nguiamba et al., 2019; Sayouba et al., 2019; Temga et al., 2015; Voula et al., 2021). The particle size distribution of the study clay is moderately consisted of clay fraction and mostly sand fraction. Indeed, the particle size distribution of the studied clays shows that the samples are constituted of mixtures in varied proportions. Position of different samples in ternary diagram for textures illustrated by **Figure 5** shows that the dominant soil texture for Boulgou was sandy silt and heavy sandy silt for Sekandé and Gaschiga excepted GA1C2. The dominance of the coarse range could be attributed to the immediate environment especially from weathering and disintegration products of sandstone (Kagonbé et al., 2020b; Voula et al., 2021). The Atterberg limits of the studied samples are shown in the Holtz and Kovacs (1981) diagram (**Figure 3**). Based on this diagram, samples BO2C2, BO3C2 and BO5C2 are lower plastic clays, samples BO1C2, SK2C2, SK1C2 and GA3C2 are medium plastic, while samples SK3C2, SK4C3, SK1C3, SPmG, GA2C2 and GA1C2 are higher plasticity clays. According to McNally (1998), the plasticity of clay materials depends to its particle size distribution and mineralogy composition. This characteristic could be also attributed to the low organic matter content and the dominance of the kaolinite mineral in the clay (Abdullahi et al., 2012).

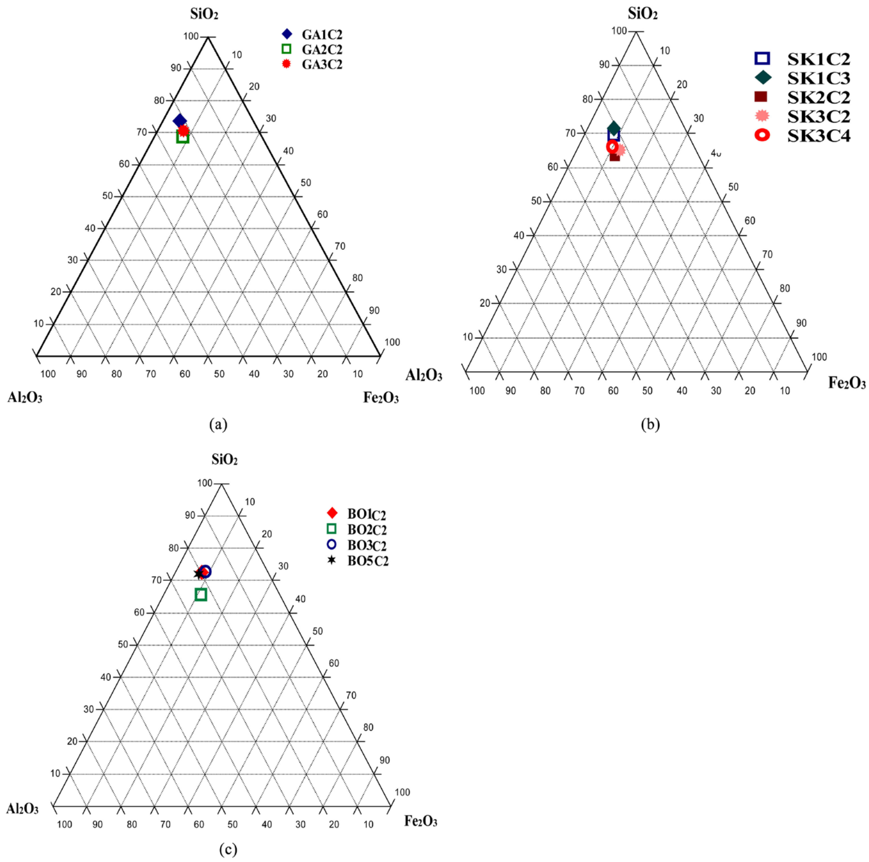

Figure 4. Geochemical composition of the studied soils in SiO_2-Al_2O_3-Fe_2O_3 diagram, (a) Gaschiga; (b) Sekandé and (c) Boulgou.

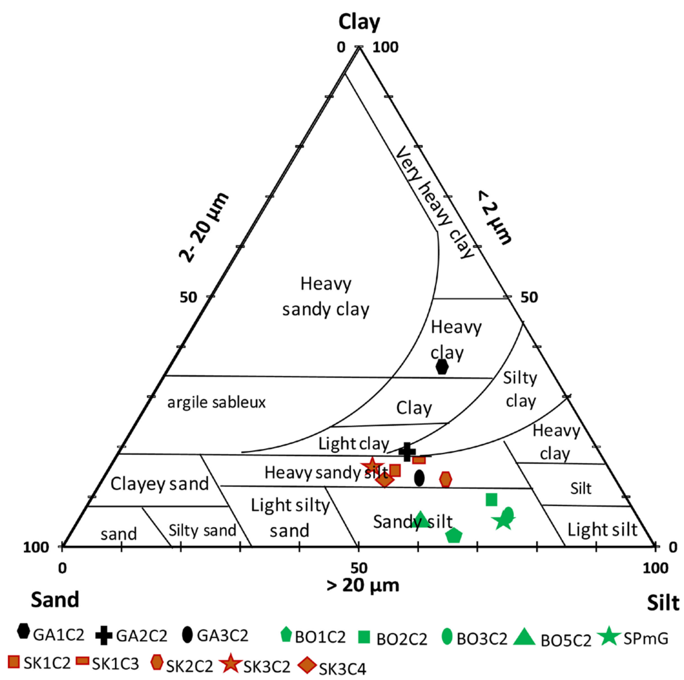

Figure 5. Ternary diagram of the studied clay materials samples according to Richer de Forges et al. (2008).

5. Conclusion

In this study, geochemical, mineralogical and physico-chemical properties of the raw clayey materials from Gaschiga, Sekandé and Boulgou in Northern Cameroon were investigated. Mineralogically, the studied raw clay materials are constituted of smectite and kaolinite as secondarily clay minerals, associated to high amount of quartz, and small amount of hematite, K-feldspath and amphibole. Monosiallitisation and bisiallitisation are the two crystallochemical processes acting in the study area. Geochemically, SiO_2, Al_2O_3 and Fe_2O_3 are the main oxides. Al_2O_3 reflects the presence of aluminosilicates and Fe_2O_3 is related to the presence of hematite. High SiO_2/Al_2O_3 ratio indicates an excess of SiO_2 in the form of quartz and the presence of 2:1 phyllosilicates of montmorillonite type towards kaolinite. Particle size analysis shows that the raw materials are mostly constituted of sand fraction (39% - 68%), followed by clay fraction (17% - 38%) and silt fraction (1% - 36%). The clay materials are moderately plastic clays, with plasticity characteristics varying between 18% and 36% and plasticity index ranging between 13% and 30%, which could be attributed to the low organic matter content and the dominance of the kaolinite mineral in the raw clay materials.

Conflicts of Interest

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

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