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Characterization of Sediment from Ourokessoum, North Cameroon: Morphostructural, Mineralogical, and Physicochemical Properties

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Abstract

The present study examines the morphological, physicochemical, and mineralogical specificity of clay sediments in the Hamakoussou Basin with the objective of exploring their potential applications. Field data collection was followed by a series of physicochemical and mineralogical tests on the clay samples. Results show that the clay layers, which range in thickness from 11 - 120 cm, exhibit gray, yellowish, or greenish colors. From a physicochemical perspective, these clay layers are found to be basic with a pH ranging from 8.5 for the higher Hama2 layer to 7.6 for the lower Hama1 layer. The sum of exchangeable bases (S) is medium to high with higher values in the Hama1 layer (53.45 meq/100g) and lower values in the Hama3 layer (17.09 meq/100g). Similarly, the cation exchange capacity (CEC) varies from 62.32 meq/100g for the higher Hama1N4 clay layer to 35.6 meq/100g for the lower Hama1N3 clay layer. Mineralogically, the clay materials are primarily composed of smectites, with illite, kaolinite, calcite, quartz, feldspar, hematite, and goethite also present. This study emphasizes the versatility of clay in various industries and scientific domains. It is known for its impermeability, plasticity, and fossil-preserving capabilities, making it a valuable material for economic, practical, and academic applications.

Keywords

Morphostructural, Sediments, Clay Layers, Sedimentary Basin, Hamakoussou

1. Introduction

Clay refers to any natural material composed of fine grains with a diameter of less than 0.004 mm, which when soaked in water can form a more or less plastic paste that can be shaped and hardened by firing (Guggenheim & Martin, 1995). They are made up of clay minerals (90% of which are of detrital origin) and non-clay minerals, which, depending on their location in space, are classified as sedimentary clays in coastal and inland basins, residual clays on hilltops and interfluves, and alluvial clays along the terraces and banks of rivers (Nkoumbou et al., 2008; Njoya et al., 2007). The formation of clay soils is a slow process of rock alteration under the influence of climate, erosion, transport, and sedimentation. Their alteration process can be physical (disintegration of primary minerals) or chemical (transformation of minerals). Some clay minerals precipitate from a solution (neoformed minerals). Clays have three possible origins: inheritance, transformation, and neoformation (Millot, 1964).

A sedimentary basin is an oval or circular depression with a flat or concave bottom and widely flared sides, of variable size, which is or has been the site of sedimentation. It is a relative depression of the Earth's crust located on an emerged continent, a continental shelf, or in an ocean, formed by thermal and/or tectonic subsidence and which collects relatively large amounts of sedimentary materials that, through diagenesis, gradually transform into stratified layers of sedimentary rock. The Hamakoussou sedimentary basin is located between latitude 9˚30' and 9˚40' and longitude 13˚20' and 13˚30' in the Bénoué department north of Garoua (**Figure 1**). It is located about 45 km north of the city of Garoua and is an integral part of the Bénoué Trough, covering an area of approximately 65 km^2 (Dejax & Brunet, 1996). It has the shape of a basin with altitudes ranging from 350 to 420 m. The highest points correspond to the ridges composed of basal sandstones (Dejax & Brunet, 1996). It is bordered by anatexis hills, quartzites, and granites, the most important of which is the rock overlooking the village of Ngoutchoumi (Popoff, 1988). Three watersheds, namely Mayo Tiel, Mayo Goulongo, and Mayo Badjouma, share this basin (Tillement, 1971), which has an asymmetrical synclinal structure with an E-W axis identical to all the basins of Northern Cameroon and Central Africa (Maurin et al.,1989; Guiraud & Maurin, 1991). In Africa, the most significant clay deposits recorded are the siderolithic deposits of the Carboniferous (Millot, 1964). Other studies indicate that sedimentary shales, alterations of syn- to post-tectonic granites and siliceous clays in Niamey, the compact and plastic clays of Calabar in Nigeria (Kogbe, 1999), alluvial clays from the plains of the Ouagadougou region in Burkina-Faso (Karfa, 2003), Palygorskite deposits in Senegal, and bentonite deposits in Algeria, Morocco, and Tunisia (Hajjaji et al., 2002; Jeridi et al., 2008) are deposits belonging to the Cretaceous-Quaternary era, characteristic of hot and humid climate. While several researchers have conducted studies on Cameroon's clay materials and their potential for valorization, they highlight the presence of talc (Nkoumbou et al., 2006; Nkoumbou et al., 2008), halloysite (Njopwouo & Wandji, 1982), and kaolin clays, which are the most significant clay deposit available in Cameroon (Njopwouo & Wandji, 1985; Elimbi et al., 2003; Njoya et al., 2006; Njoya et al., 2007; Pialy et al., 2008; Nkoumbou et al., 2009; Ekosse, 2010).

The color of clays varies depending on their concentration of iron oxide and they are used by humans in various applications thanks to their different mineralogical, physico-chemical, and textural properties, including construction and engineering (barrier material), ceramics and pottery (raw material for ceramics), agriculture (soil improvement), geotechnical engineering (foundation support), brick and tile production (construction material), and more (Brunet, 1986; Konta, 1995; Harvey & Murray, 1997; Ekosse, 2000; Carretero, 2002). Clay minerals are also found as catalysts, particularly in the pharmaceutical industry, or as membranes for filtration processes in the agri-food industry (Murray, 2000).

Due to their easy exploitation and multiple uses, clays can be a treasure for African countries, particularly Cameroon, which values the clays of the Logone Valley for construction materials and pottery (Kamgang et al., 2011; Temga et al., 2015; Temga, 2015). Previous studies on the Hamakoussou Sedimentary Basin indicate that it is composed of geological formations such as conglomerates, sandstones, siltstones, argillites, and carbonates that have been affected by volcanic eruptions (Ntsama et al., 2014; Koch, 1959; Popoff, 1988; Valášková & Martynkova, 2012; Konga, 2017). The morphology of the Hamakoussou Sedimentary Basin is a syneclinal with asymmetrical flanks, making research on the site cumbersome and therefore studies on its clays are little known. It is in this context that the clays of the Hamakoussou Sedimentary Basin have raised a deeper reflection in order to carry out a macromorphological, physico-chemical, and mineralogical characterization while presenting an economic interest.

2. Materials and Methods

2.1. Materials

The 1:50,000 scale topographic map of Garoua was used to delimit the study area, consisting of the Hamakoussou Sedimentary Basin located between latitude 9˚30' and 9˚40' and longitude 13˚20' and 13˚30' in the Benoue department north of Garoua (**Figure 1**). A Garmin 64 S GPS was used to record coordinates in the field, a compass was used for orientation, shovels were used to refresh soil trenches and collect samples, and plastic bags were used to store samples.

2.2. Methods

On the field, the work consisted of macroscopic description of the outcrops, followed by sampling of eight clay samples (**Figure 2**) at different locations on three lithological logs, which were labeled (**Table 1**), dried, and preserved in plastic bags for laboratory analysis (Geolabs and LABASCE). The samples were ground into powder using a zirconium crusher for 10 to 20 seconds and the material was sieved through a 60-mesh sieve. The sample powders were then pulverized with an agate mortar and pestle and smear mounts were prepared on low background silicon discs for analysis. The samples were analyzed at the Geolabs laboratory in Canada with Co radiation at 40 KV and 45 Ma. Mineralogical analyses were carried out by X-ray diffraction. Physico-chemical analyses focused on pH, determined by the ratio of (clay/water: 1/2.5) using a LPH 330T type electrode pH meter, cation exchange capacity (CEC) determined by the complexation method with thio-urea (H2N-CS-NH2) of sodium, and exchangeable base determined by the Metson method.

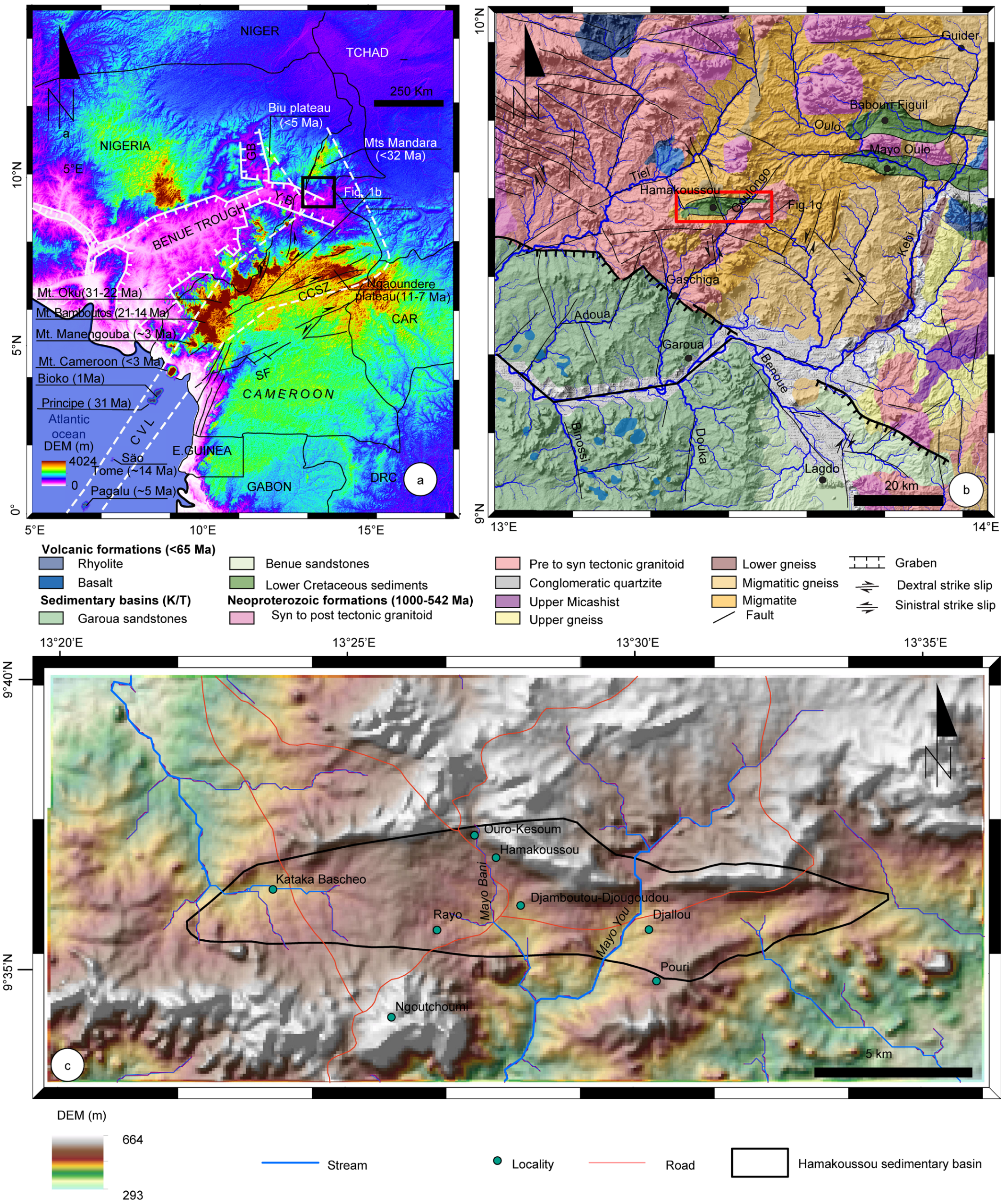

Figure 1. Location of study area showing (a) Central Africa DEM, including the Cameroon landform surface dissected by the main tectonic features that cross cut it (Mvondo et al., 2024), YB: Yola branch, GB: Gongola branch, CCSZ: Cameroon Center Shear Zone, SF: Sanaga Fault, CVL: Cameroon Volcanic Line, CAR: Central African Republic, DRC: Democratic Republic of Congo; (b) Geological map of Garoua (Abate et al., 2019); (c) DEM of Hamakoussou sedimentary basin.

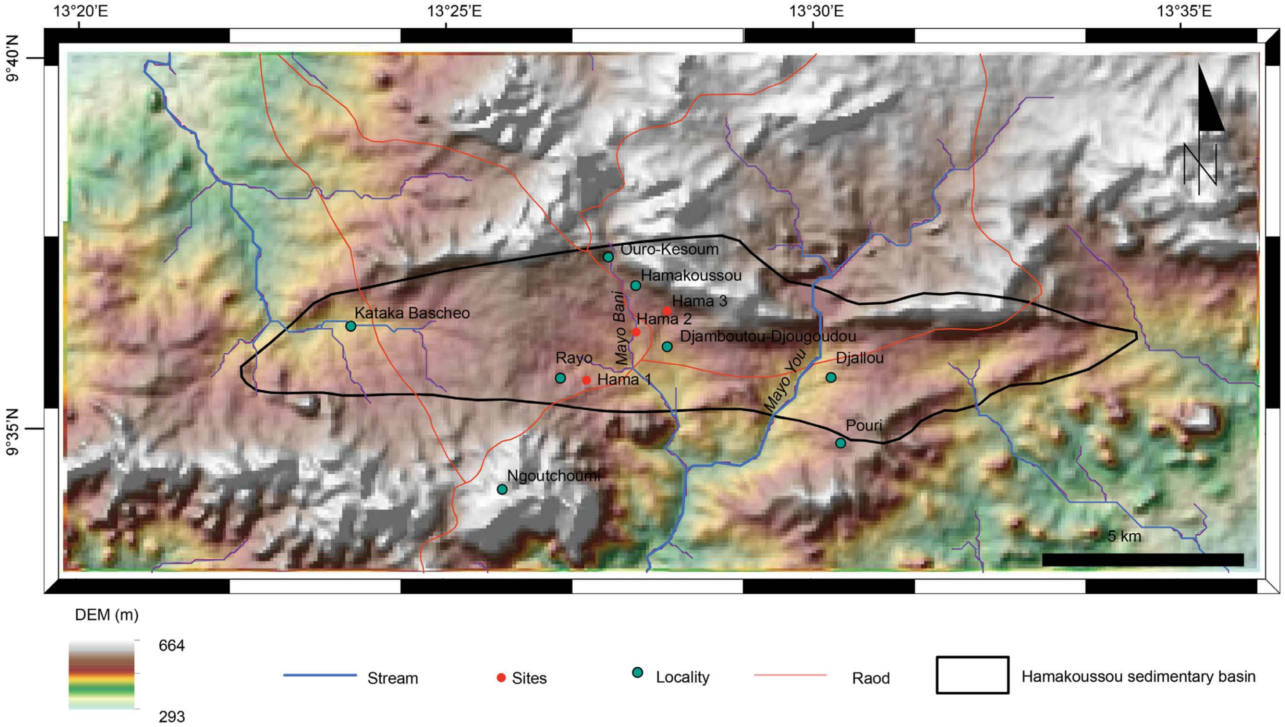

Figure 2. Sampling map.

Table 1. Samples codes for analysis.

Samples codes	Samples to be analysed
Hama1N3	Lithological Log of Hama1
Hama1N4	lithological Log of Hama1
Hama2N3	lithological Log of Hama2
Hama2N4	lithological Log of Hama2
Hama3N3	Log lithologique Hama3
Hama3N9	lithological Log of Hama3
Hama3N11	lithological Log of Hama3
Hama3N12	lithological Log of Hama3

3. Results

3.1. Macromorphological Characterization of Clay Layers

The observations made in the field, followed by descriptions, made it possible to identify three sampling points that serve as a basis for illustrating three lithological logs on the Hama1, Hama2, and Hama3 sites (Figure 2).

3.1.1. Lithological Log of Hama1

The Hama1 lithological log, with a thickness of 156 cm, was carried out in the locality of Ouro Kessoum, at geographic coordinates N09˚36'32", E013˚28'19.63" and an altitude of 377 m. The observation made from top to bottom shows four levels (N) of differentiation (**Figure 3**). N1 (0 - 55 cm) shows a fine-grained, dark gray sandy material with ferruginous nodules, and the boundary with the lower level is relatively clear. N2 (55 to 95 cm) shows a coarse-grained material with diameters ranging from 2 to 20 cm packed in a fine, light gray material. Ferruginous nodules are present, and the boundary is clear. N3 (95 to 145 cm) is a dark gray (2.5Y 4/1), compact, and very hard clay material containing millimeter-sized fossils with a progressive boundary where the sample (Hama1N3) was taken. N4 (145 to 156 cm) is a compact and very hard olive-yellow (5Y 6/8) clay material with a progressive boundary and was the subject of the sample collection (Hama1N4).

We observe that the lithological log of the Hama1 site consists of four (4) levels, with the first two levels being fine and coarse-grained sandy materials, and the last two levels consisting of dark gray and olive-yellow clay materials. In this log, only the clay levels were sampled for laboratory analysis, and their samples are presented in photo 1. These levels are level 3 (Hama1N3) and level 4 (Hama1N4).

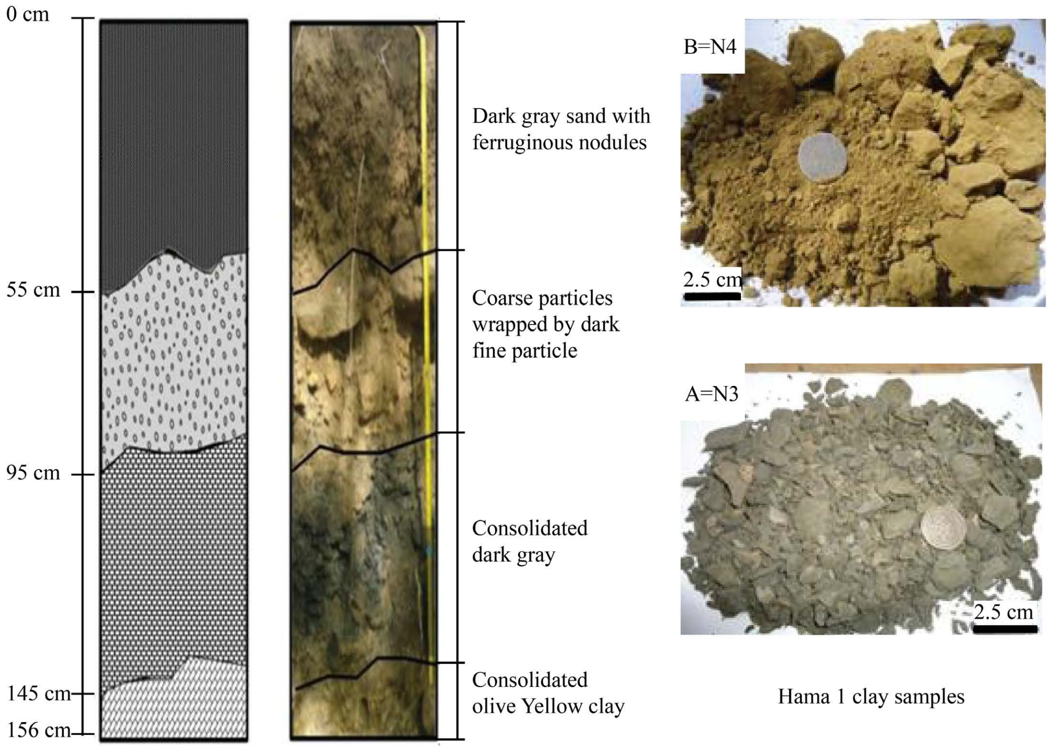

Figure 3. Lithological log of the Hama1 site 1. Photo 1: Hama1 clay samples. (A = N3, B = N4).

3.1.2. Lithological Log of the Hama2

The lithological log of the Hama2 site was carried out at the small village of Djamboutou, at the coordinates N09˚36'28.8" E013˚23'03.7" and an altitude of 377 m, with a thickness of 229 cm. The description, from bottom to top, shows 4 levels (N) of differentiation (**Figure 4**). N1 (0 - 70 cm) consists of fine-grained sandy materials, dark gray in color, with ferruginous nodules, and a clear boundary. N2 (70 - 152 cm) consists of coarse-grained materials (2 - 10 cm in diameter) packed in a fine material, light gray in color speckled with white, with calcareous nodules present, and a clear boundary. N3 (152 - 202 cm) presents clay materials, whitish in color speckled with light olive brown (2.5y 5/4), with calcareous nodules, and is less compact and fragile, with a gradual boundary. Sample Hama2N3 was taken from this layer. Finally, level 4 (202 - 229 cm) consists of clay materials, light olive brown in color (2Y5 5/6), compact and very hard, with a gradual boundary. Sample Hama1N4 was taken from this layer for laboratory analysis.

In summary, the lithological log of Hama2 consists of four (4) levels, with the first two stages being fine and coarse-grained sandy materials, and the last two levels being clayey in nature with whitish color speckled with light olive brown and light olive brown. In this log, only the clayey levels were sampled for laboratory analysis (photo 2).

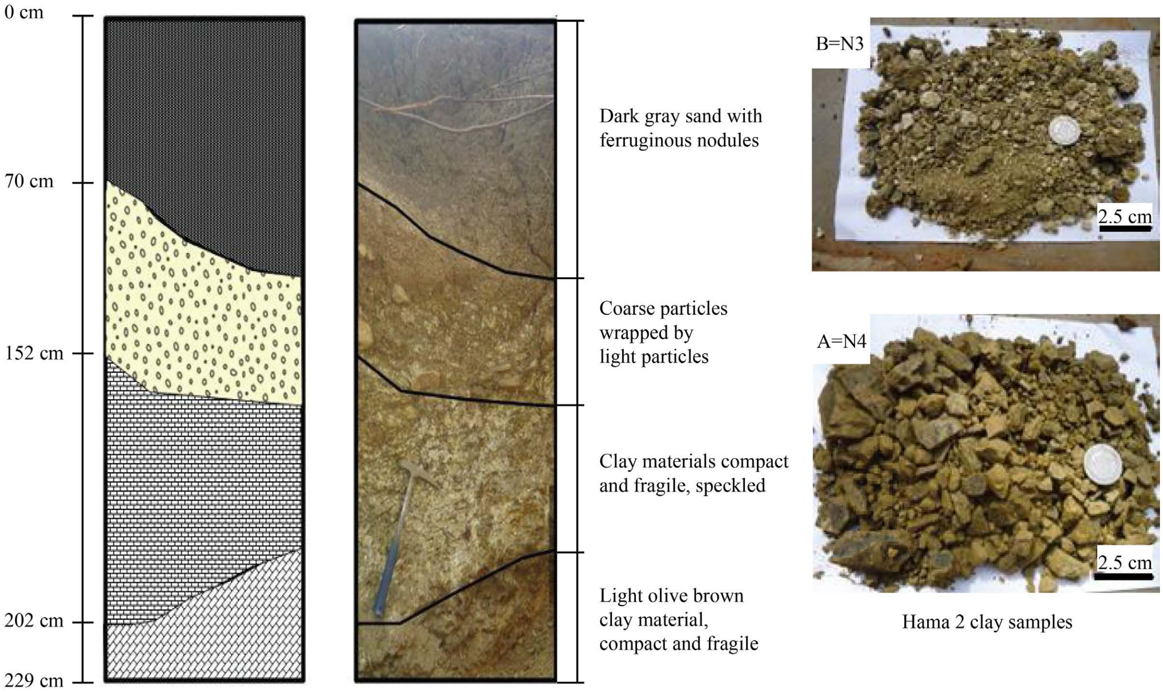

Figure 4. Lithological log of the Hama2. Photo 2: Hama2 clay samples (A = N4, B = N3).

3.1.3. Lithological Log of the Hama3

The lithological log of Hama2 is located in Djamboutou at the coordinates N09˚36'11.7" E013˚27'37.5", at an altitude of 370 m and has a thickness of 388 cm. Field observations allow for the subdivision of this log into two subsets. The first subset consists of nine levels, more or less altered, with a thickness of 277 cm (Figure 5). The description, from top to bottom, shows that N1 (0 - 24 cm) has fine-grained sandy materials, with the presence of angular to subangular sediments, dark gray in color, with a clear boundary. N2 (24 - 51 cm) has coarse-grained materials (2 - 20 cm in diameter) packed in a fine material, light gray in color, with ferruginous nodules present, and a clear boundary. N3 (51 - 101 cm) has clayey materials, light gray in color speckled with white (5y 7/2), with calcareous nodules present, and less compact and fragile, with a gradual boundary. Sample Hama3N3 was taken from this layer. N4 (101 - 114 cm) consists of fine sandstone, yellow olive in color (5y 6/8), compact and very hard, with a clear boundary. N5 (114 - 129 cm) consists of weathered sandstone, yellow olive in color (5Y 6/8), compact, with a clear boundary. N6 (129 - 149 cm) consists of fine sandstone, greenish in color, compact and very hard, with a clear boundary. N7 (149 - 153 cm) consists of weathered sandstone, yellow olive in color (5Y 6/8), compact, with a clear boundary. N8 (153 - 157 cm) consists of fine sandstone, yellow olive in color (5Y 6/8), compact and very hard, with a clear boundary, and N9 (157 - 277 cm) consists of clayey materials, pale olive in color (5Y 6/3), with calcareous nodules present, less compact and fragile, with a gradual boundary. Sample Hama3N9 was taken from this layer (photo 3).

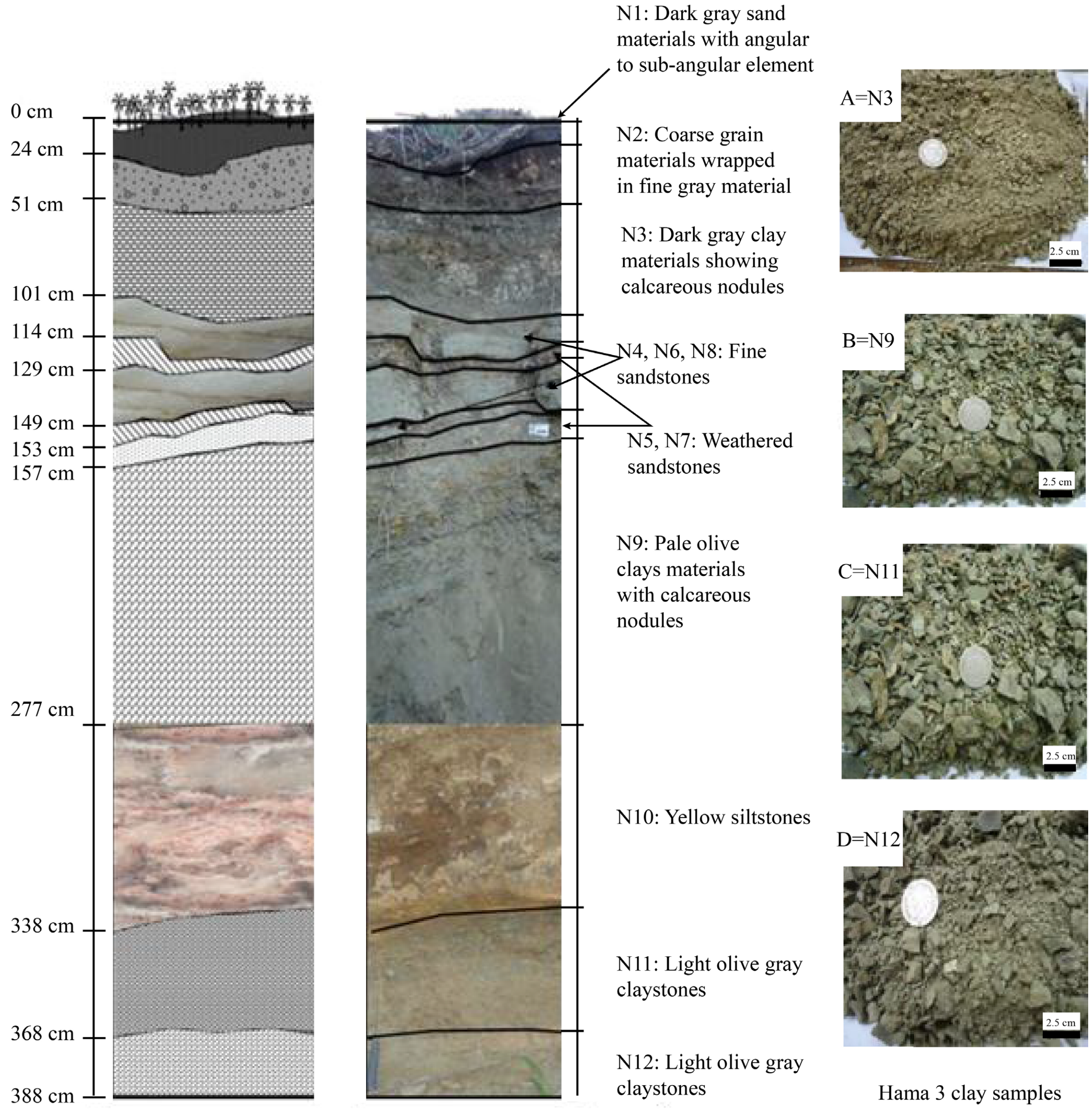

Figure 5. Lithological log of the Hama3. Photo 3: Hama3 clay samples (A = N3, B = N9, C = N11, D = N12).

The second subset consists of three levels, with a thickness of 61 cm. They are located 10 m away and continue towards the North of the lithological log. Due to alteration, the three (3) base levels are well visible towards the top. The description reveals that N10 (277 - 338 cm) consists of Siltstone, yellowish in color, compact and very hard, with a clear boundary. N11 (338 - 368 cm) has clayey materials, light gray olive in color (5Y 6/2), compact and hard, with a gradual boundary. Finally, N12 (368 - 388 cm) has clayey materials, light gray olive in color (10y 6/2), compact and hard, with a gradual boundary. Samples Hama3N11 and Hama3N12 were taken from layers N11 and N12 respectively (photo 3b).

In conclusion, the macromorphological study of the sedimentary basin of Hamakoussou, through three (3) lithological logs, shows that the sampling sites consist of levels N1 (fine-grained sandy materials, dark gray in color), N2 (coarse-grained materials, light gray in color), and N3 (clayey materials that differ in color and sometimes have the presence of limestone). The eight samples of clayey materials taken for laboratory analysis are recorded in Table 2.

Table 2. Distribution of samples by lithological logs.

Log Hama1		Log Hama2		Log Hama3	
Sample	Thickness	Sample	Thickness	Sample	Thickness
Hama1N3	50 cm	Hama2N3	50 cm	Hama3N3	50 cm
Hama1N4	11 cm	Hama2N4	27 cm	Hama3N9	120 cm
				Hama3N11	30 cm
				Hama3N12	20 cm

3.2. Physico-Chemical Characterization of Clayey Materials

3.2.1. pH of Clayey Materials from Lithological Logs

The physico-chemical analyses were conducted on eight (8) samples of clayey layers collected from the three (03) lithological logs: Hama1 (Hama1N3, Hama1N4), Hama2 (Hama2N3, Hama2N4), and Hama3 (Hama3N3, Hama3N9, Hama3N11, Hama3N12). The results showed that the clayey materials from the lithological log Hama1 have a basic pH (Figure 6). However, the clayey layer Hama1N3 has a slightly more basic pH (pH = 8) than that of Hama1N4 (pH = 7.6). Two (2) clayey layers were analyzed from the Hama2 lithological log (Hama2N4, Hama2N3). The Hama2 log has a strongly basic pH (8.5) on both samples Hama2N4 and Hama2N3 (Figure 7). Four clayey layers were analyzed on the Hama3 site (Hama3N12, Hama3N11, Hama3N9, and Hama3N3). The physico-chemical analyses conducted on the Hama3 samples show that it has a basic pH (Figure 8). The pH of these clayey materials varies greatly from one sample to another and remains in the range of 8 and 8.3.

In conclusion, the pH of the samples collected from the clayey layers is basic, with higher values observed in the Hama2 log, followed by the Hama3 log and finally the Hama1 log.

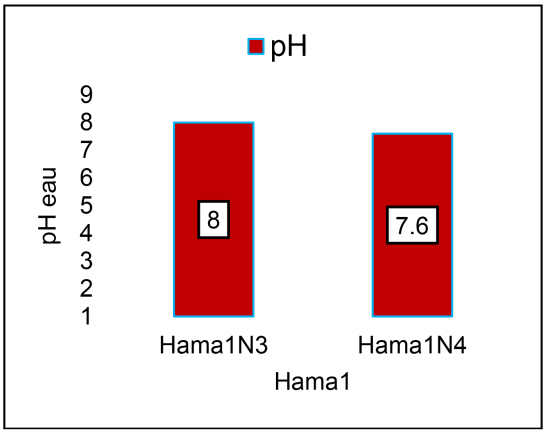

Figure 6. pH of the lithological log Hama1.

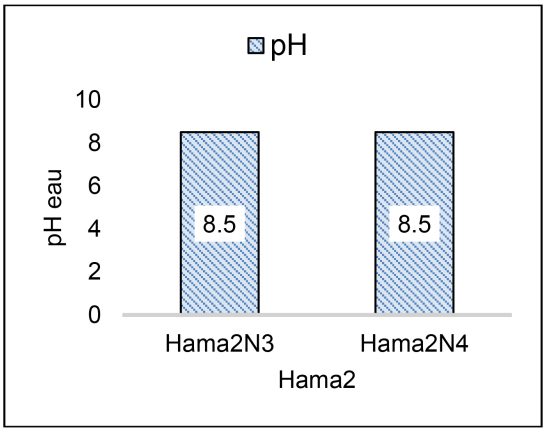

Figure 7. pH of the lithological log Hama2.

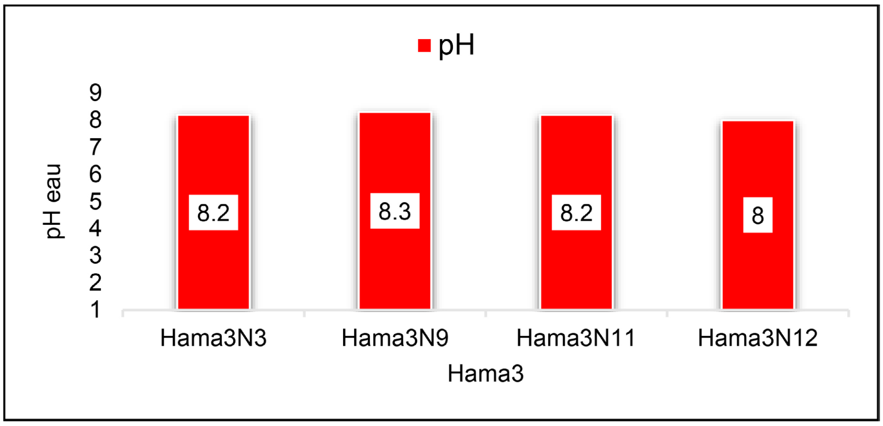

Figure 8. pH of Hama3 sample.

3.2.2. Sum of Bases of the Clayey Materials in the Lithological Log

The clayey materials analyzed in the lithological log Hama1 have higher Ca^{2+} contents in the Hama1N4 sample (36.60 meq/100g) and lower contents in the Hama1N3 sample (21.3 meq/100g). The Mg^{2+} content (7 meq/100g) is high and constant in all analyzed samples. The K^{+} content is very high in the clayey materials, with the Hama1N4 sample (8.97 meq/100g) being 4 times higher than the Hama1N3 sample (2.12 meq/100g). The Na^+ content (0.88 meq/100g) in the Hama1N4 sample is high, and the Na^{2+} content (0.79 meq/100g) in the Hama1N3 sample is also high, with the Hama1N4 sample having a slightly higher content than the Hama1N3 sample. The exchangeable bases sum is very high in both samples Hama1N3 (31.28 meq/100g) and Hama1N4 (53.45 meq/100g). However, the Hama1N4 sample has a nearly twice as high saturation sum as the Hama1N3 sample (**Figure 9**). The element contents of the clayey materials from the lithological log Hama2 (**Figure 10**) indicate that the Ca^{2+} content of the clayey materials (14.6 meq/100g) is high in the Hama2N3 sample and very high (25.2 meq/100g) in the Hama2N4 sample, twice that of the Hama2N3. The Mg^{2+} content is high in the Hama2N4 sample (4.28 meq/100g) and very high in the Hama2N3 sample (9.2 meq/100g), twice as much as in the Hama2N4 sample. The K^+ content is average in the Hama2N3 sample (0.36 meq/100g) and very high (1.45 meq/100g) in the Hama2N4 sample, 4 times higher than in the Hama2N3 sample. The Na^+ content of the clayey materials at the Hama2 site is a low 0.23 meq/100g in the Hama2N3 sample and high (0.79 meq/100g) in the Hama2N4 sample, 3 times higher than in the Hama2N3 sample. The exchangeable bases sum is high in the Hama2N4 sample (21.13 meq/100g) and very high in the Hama2N3 sample (34.99 meq/100g). The clayey materials analyzed at the Hama3 site have variable contents (**Figure 11**). The Ca^{2+} content of the clayey materials is high in Hama3N9 sample (10.60 meq/100g) and very high in the Hama3N3 (30.80 meq/100g), Hama3N11 (24 meq/100g), and Hama3N12 (37 meq/100g) samples. The Ca^{2+} content of the Hama3N12 sample is 3 times higher than that of the Hama3N9 sample and much higher than that of the Hama3N3 and Hama3N11 samples. The Mg^{2+} content is high in the Hama3N3 (5.20 meq/100g), Hama3N9 (4.48 meq/100g), and Hama3N12 samples (7.40 meq/100g) and very high in the Hama3N11 sample (8.60 meq/100g). The Mg^{2+} content varies in a sawtooth manner in the clayey materials. The K^+ content is high in the Hama3N11 (0.71 meq/100g) and Hama3N12 samples (1 meq/100g) and very high in the Hama3N3 (2.89 meq/100g) and Hama3N9 samples (1.38 meq/100g). The K^+ content also varies in a sawtooth manner. The Na^+ content of the clayey materials in the Hama3 lithological log is low in the Hama3N11 (0.17 meq/100g) and Hama3N12 (0.23 meq/100g) samples and medium in the Hama3N3 (0.41 meq/100g) and Hama3N9 (0.63 meq/100g) samples. The Na^+ content varies in a sawtooth pattern in these clayey materials. It is evident that the exchangeable bases' sum is high in the Hama3N9 sample (17.09 meq/100g) and very high in the Hama3N3 (39.30 meq/100g), Hama3N11 (33.49 meq/100g), and Hama3N12 (45.63 meq/100g) samples. The Hama3N12 sample is three times richer in sum of bases than the Hama3N9 sample and remains higher than the Hama3N11 and Hama3N3 samples. The sum of bases in the clayey materials of the Hama3 lithological log varies in a sawtooth pattern.

In conclusion, the sum of exchangeable bases (S) is higher in the Hama1 layer (53.45) and lower in the Hama3 layer (17.09). The decreasing order of layers is as follows: Hama1N4, Hama3N12, Hama3N3, Hama2N3, Hama3N11, Hama1N3, Hama2N4, and Hama3N9.

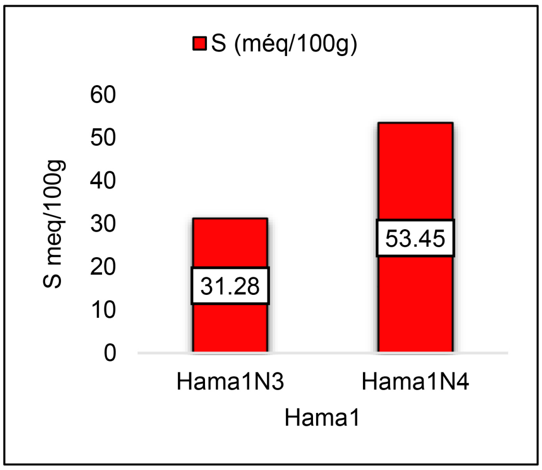

Figure 9. Sum of bases in the Hama1 log.

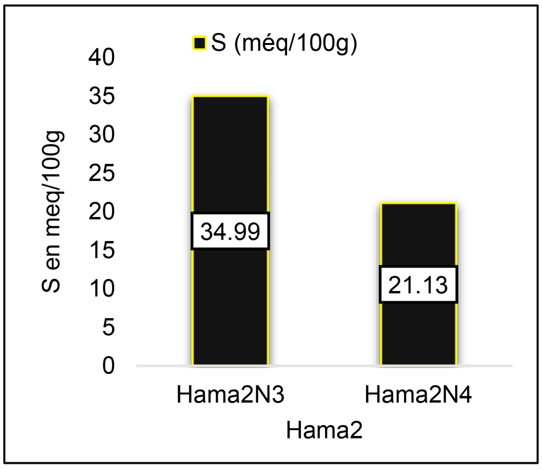

Figure 10. Sum of bases in the Hama2 log.

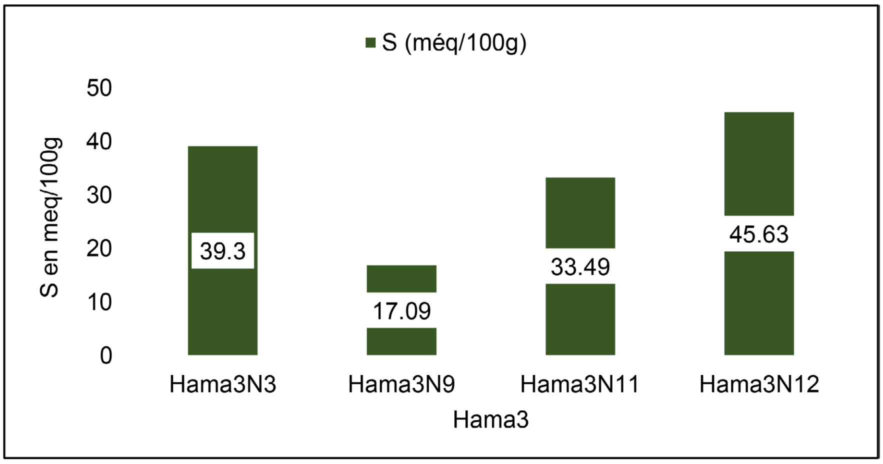

Figure 11. Sum of bases in the Hama3 log.

3.2.3. CEC of the Clayey Materials in the Lithological Log

The CEC of the Hama1 lithological log is weaker in Hama1N3 (35.6 meq/100g) and very strong in Hama1N4 (62.32 meq/100g). However, the Hama1N4 sample has a content almost 2 times higher than that of the Hama1N3 sample (**Figure 12**). The saturation rate is high in the Hama1 lithological log. The Hama1N3 sample (88%) has a slightly stronger saturation rate than that of Hama1N4 (86%). The CEC of the Hama2 site samples is strong (**Figure 13**). The cation exchange capacity of the Hama2N4 sample (46 meq/100g) is higher than that of the Hama2N3 sample (39.6 meq/100g). The saturation rate of the Hama2N3 sample (88%) is almost two times higher than that of Hama2N4 (46%). The CEC of the Hama3 lithological log samples is high (**Figure 14**) for Hama3N3 (45.84 meq/100g), Hama3N9 (46.72 meq/100g), Hama3N11 (46.32 meq/100g), and Hama3N12 (51.2 meq/100g). However, it remains higher in the Hama3N12 sample. The saturation rate of the Hama3N9 sample (37%) is two times lower than for the Hama3N3 (86%), Hama3N12 (89%), and Hama3N11 (72%) samples. La capacité d'échange cationique des échantillons du log lithologique Hama3 est forte (**Figure 15**). Hama3N3 (45.84 méq/100g); Hama3N9 (46.72 méq/100g); Hama3N11 (46.32 méq/100g) et Hama3N12 (51.2 méq/100g). However, it remains higher in the Hama3N12 sample. The saturation rate of the Hama3N9 sample (37%) is two times lower than for the Hama3N3 (86%), Hama3N12 (89%), and Hama3N11 (72%) samples.

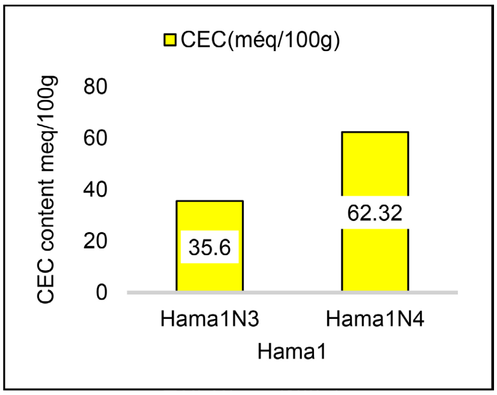

Figure 12. CEC of Hama1.

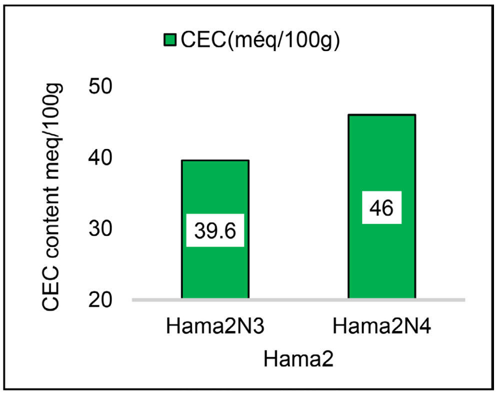

Figure 13. CEC of Hama2.

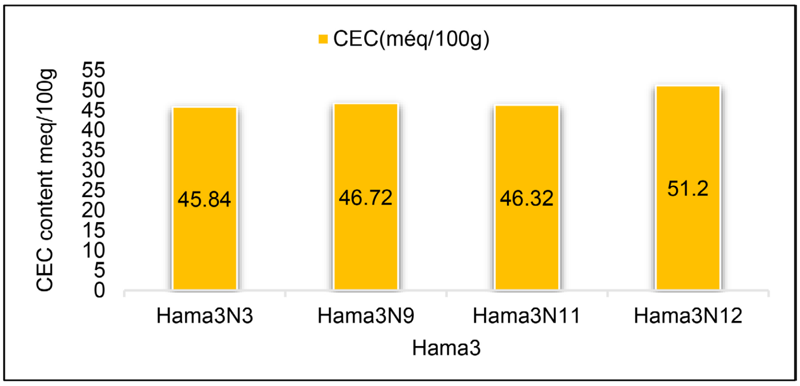

Figure 14. CEC of Hama3.

In conclusion, the CEC values range from 62.32 to 35.6 and are higher in Hama1N4 and lower in Hama1N3. The decreasing order is as follows: Hama1N4, Hama3N12, Hama3N9, Hama3N11, Hama2N4, Hama3N3, Hama2N3, and Hama3N3.

3.3. Mineralogical Characterization of Clay Materials

The mineralogical analysis of the diffractograms carried out on eight (08) samples (Table 3) identified eight (08) minerals in all the samples. For the Hama1 site, these minerals are smectite, feldspar, illite, kaolinite, quartz, hematite, and goethite. The diffractogram of the Hama1N3 sample (Figure 15) shows that this clay level is mainly composed of smectite and accessory feldspar, quartz, hematite, and kaolinite. Furthermore, smectite, feldspar, and quartz are well differentiated, unlike other minerals. On the other hand, the diffractogram of the Hama1N4 sample (Figure 16) shows that this clay level is mainly composed of smectite and accessory quartz, kaolinite, goethite, and illite. Smectite and quartz are well differentiated, unlike other minerals. Smectite and quartz are well crystallized, while kaolinite, illite, and goethite are poorly crystallized.

Regarding the Hama2 site, the results presented in Figure 17 and Figure 18 show that they are composed of smectite, calcite, illite, kaolinite, quartz, and goethite. The diffractogram of the Hama2N3 sample (Figure 17) shows that this clay level is mainly composed of smectite associated with kaolinite and accessory calcite, illite, goethite, and quartz. Smectite, kaolinite, and calcite are more or less well differentiated. The diffractogram of the Hama2N4 sample (Figure 19) shows that this clay level is mainly composed of smectite associated with kaolinite, accessory quartz, calcite, and goethite. The peaks of minerals such as smectite and kaolinite are well differentiated, unlike those of calcite, quartz, and goethite, which are less differentiated.

For the Hama3 site represented by Figure 20, Figure 21 and Figure 22 are composed of smectite, calcite, feldspar, illite, quartz, hematite, and goethite.

The Hama3N3 sample (Figure 20) shows that this clay level is mainly composed of smectite associated with illite and accessory calcite, goethite, quartz, hematite, and feldspar. Smectite, illite, and calcite are more or less well differentiated, unlike other minerals. The Hama3N9 sample (Figure 21) shows that this clay level is mainly composed of smectite associated with illite and accessory calcite, feldspar, quartz, and goethite. Smectite, calcite, and illite are well differentiated, unlike the peaks of feldspar, quartz, and goethite, which are less differentiated. The Hama3N11 sample (**Figure 22**) shows that this clay level is mainly composed of smectite associated with illite and accessory calcite, quartz, hematite, and feldspar. Smectite, calcite, illite, and quartz are well differentiated, unlike hematite, feldspar, and goethite, which are less differentiated. The total Hama3N12 sample (**Figure 22**) shows that this clay level is mainly composed of smectite associated with illite and accessory calcite, hematite, goethite, and quartz. Smectite, illite, calcite, and quartz are more or less well differentiated, unlike hematite and goethite, which are less differentiated.

Table 3. Récapitulatif des données minéralogiques.

Clay minerals	Lithological log of Hama1		Lithological log of Hama2		Lithological log of Hama3			
	Hama1N3	Hama1N4	Hama2N3	Hama2N4	Hama3N3	Hama3N9	Hama3N11	Hama3N12
Smectite	++++	++++	++++	++++	++++	++++	++++	++++
Kaolinite	+	+	++++	++++				
Illite		+	++		+++	++++	+++	+++
Calcite			+++	+	+++	++	+++	+++
Quartz	+++	+++	++	++	++	++	++	++
Goethite		+	++	+	++	+	+	++
hématite	++				+	+	+	+

++++ = abondant, +++ = moyen, ++ = faible, + = trace ++++ = abondant, +++ = moyen, ++ = faible, + trace.

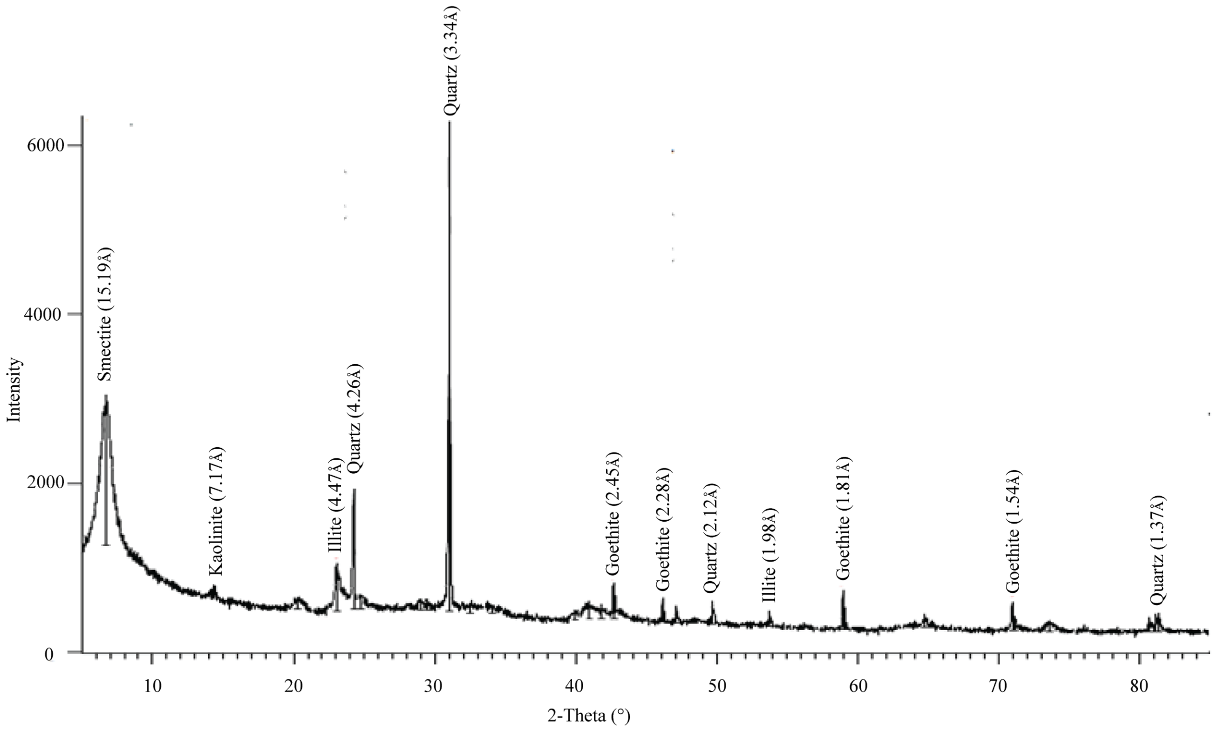

Figure 15. Diffractogram of the total fraction of the Hama1N3 sample.

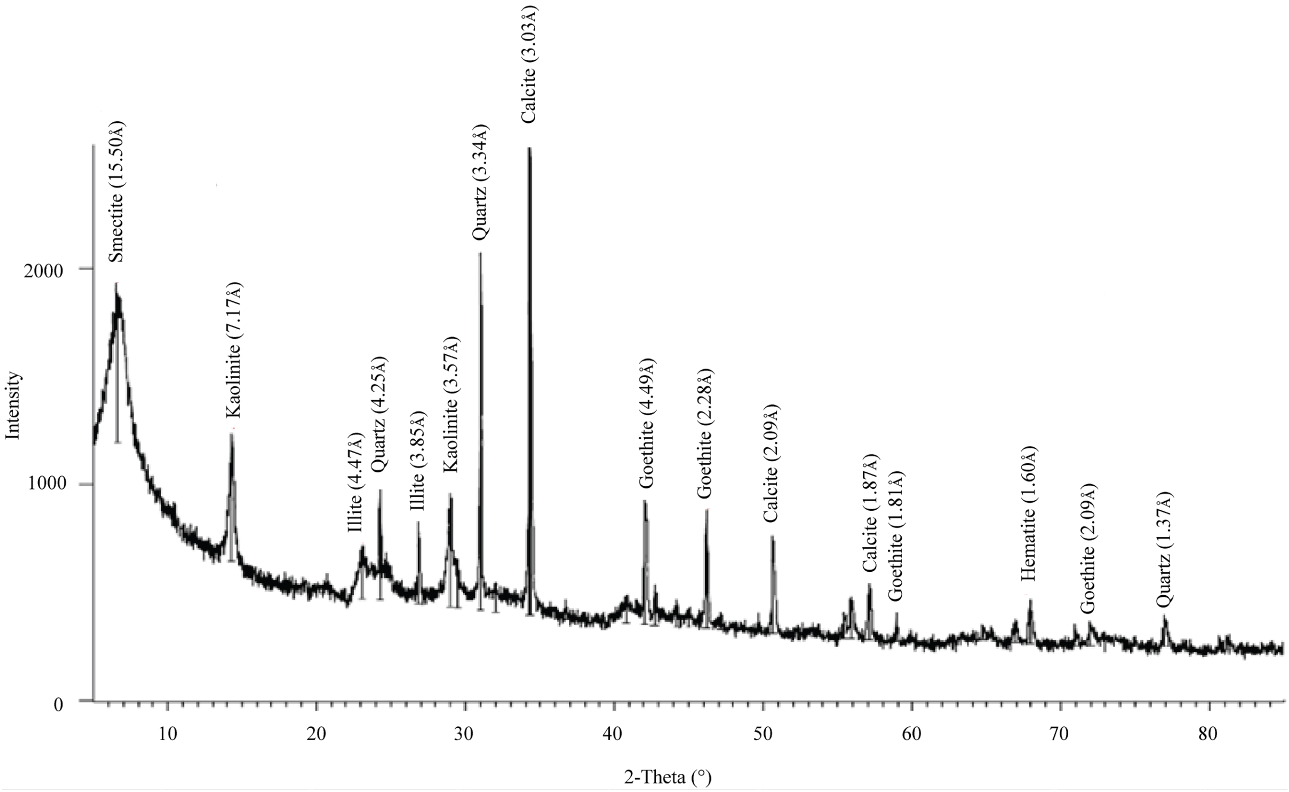

Figure 16. Diffractogram of the total fraction of the Hama1N4 sample.

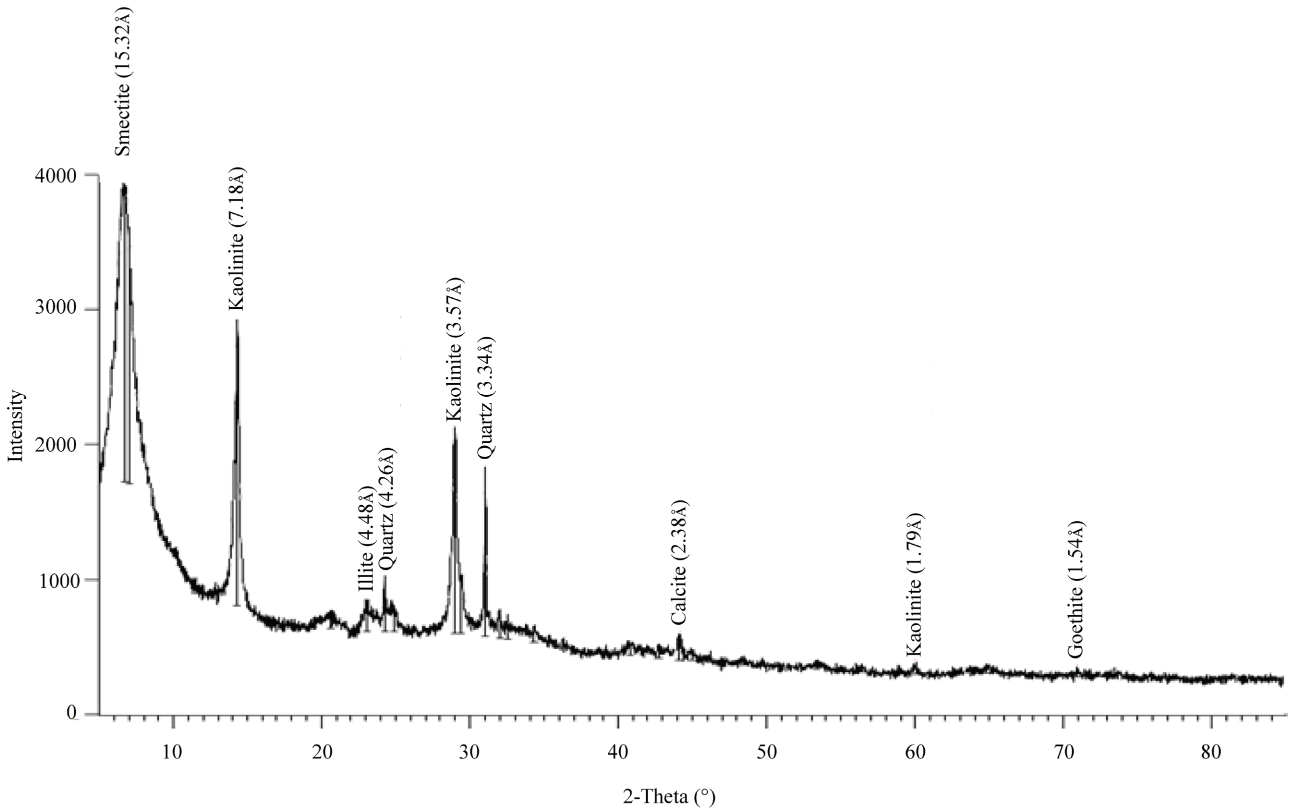

Figure 17. Diffractogram of the total fraction of the Hama2N.

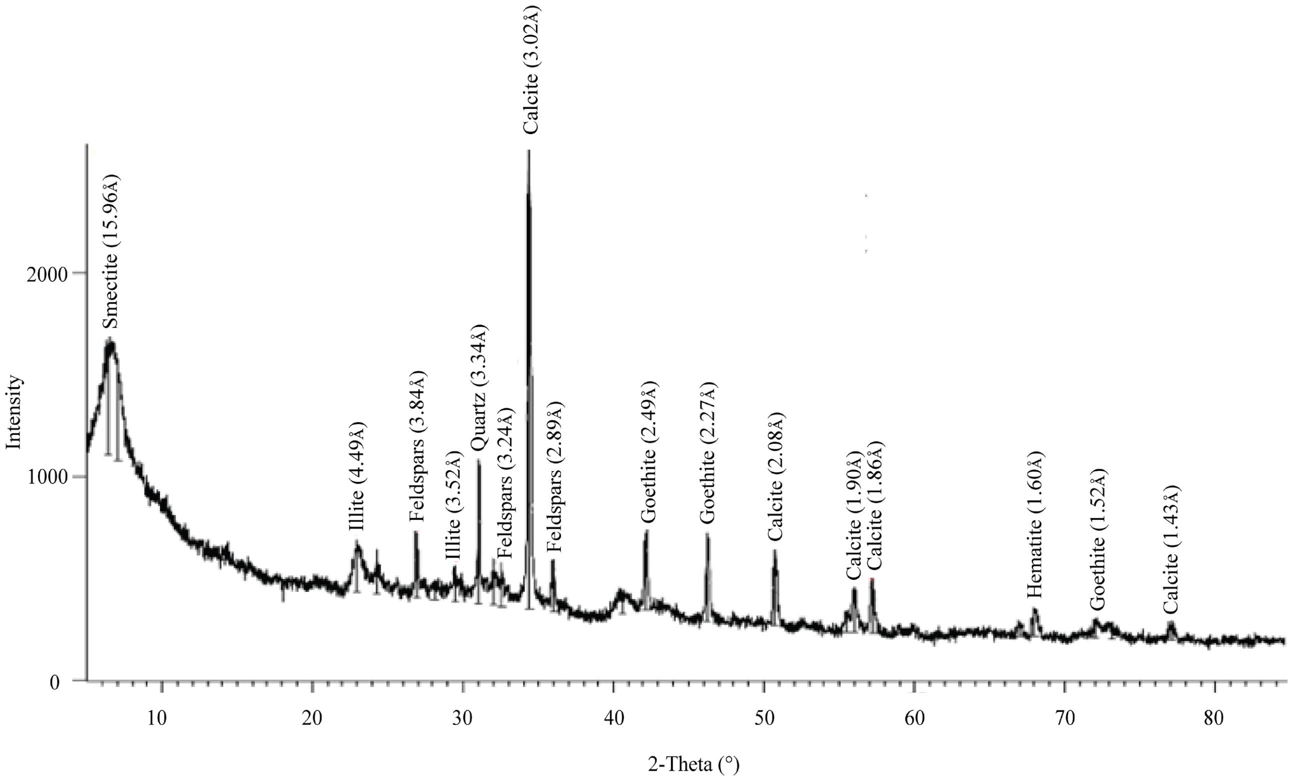

Figure 18. Diffractogram of the total fraction sample from Hama2N4.

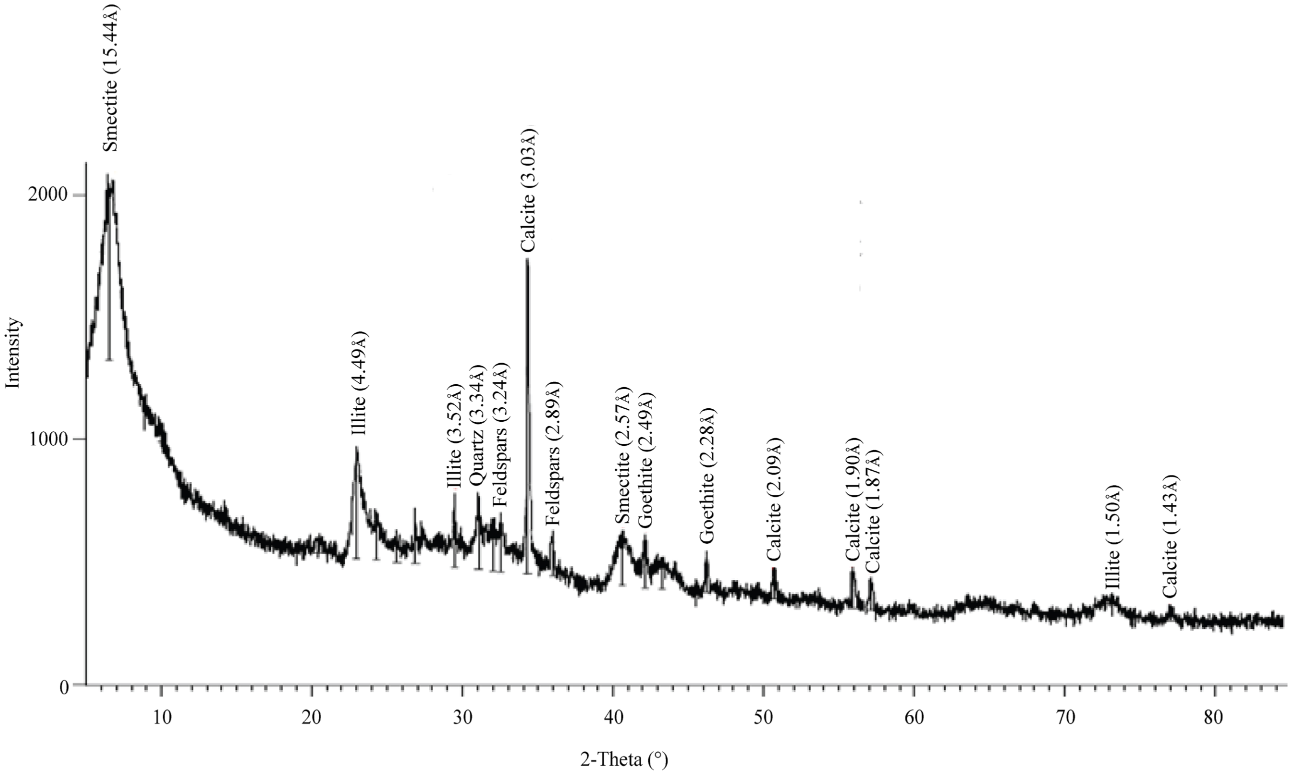

Figure 19. Diffractogram of the total fraction sample from Hama3N3.

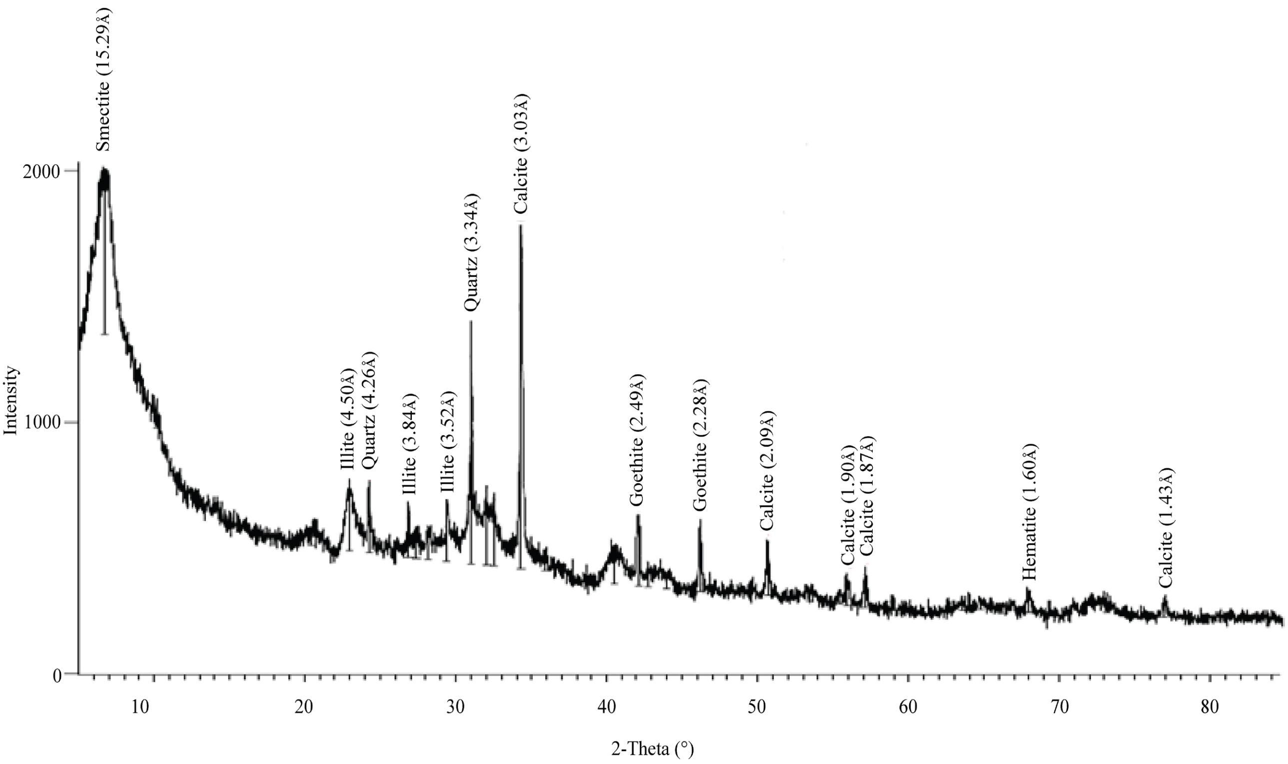

Figure 20. Diffractogram of the total fraction sample from Hama3N9.

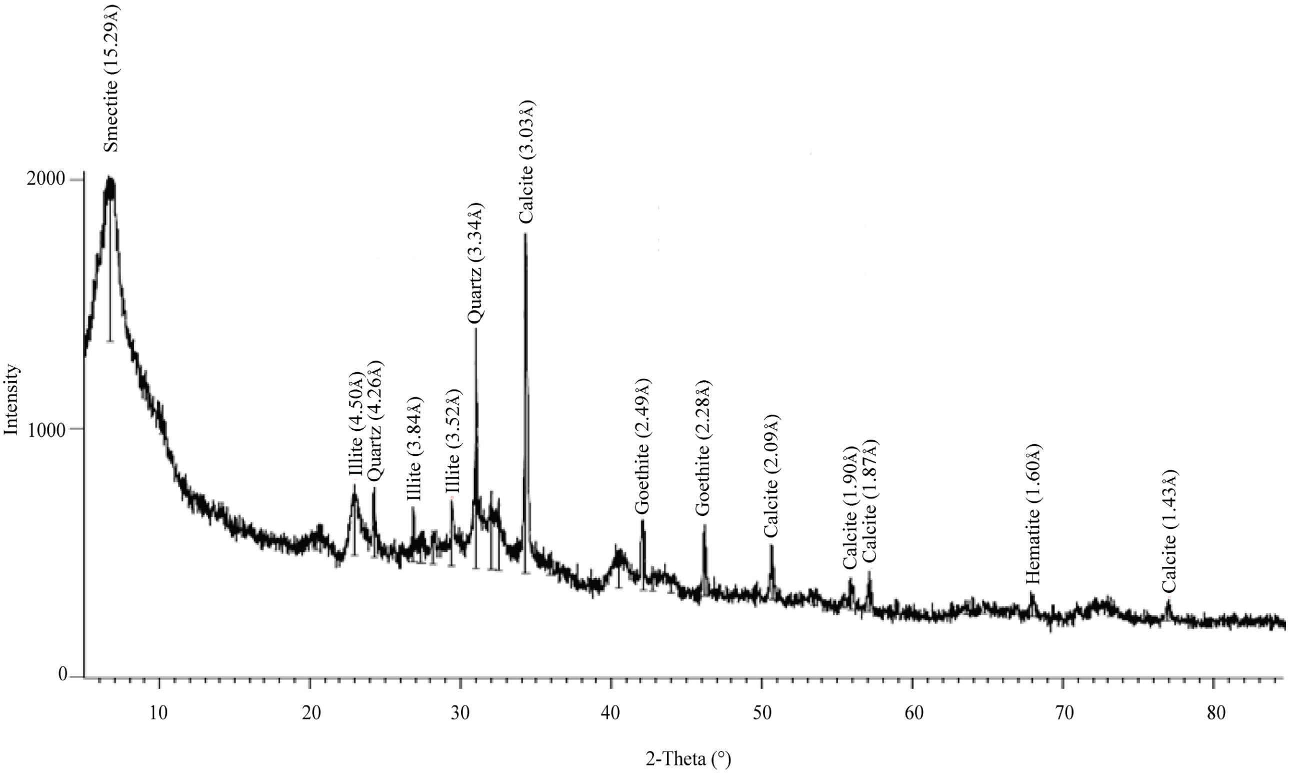

Figure 21. Diffractogram of the total fraction sample from Hama3N11.

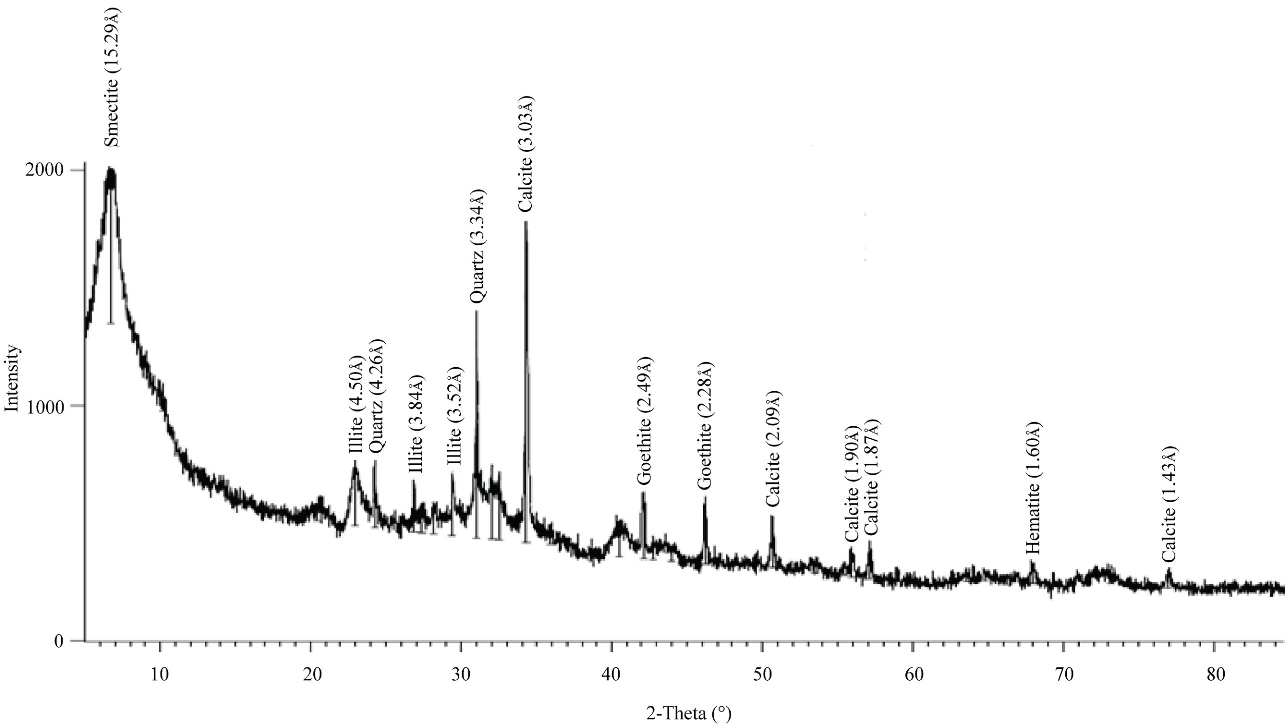

Figure 22. Diffractogram of the total fraction sample from Hama3N12.

In summary, the clay materials at the study site have a mineralogical suite consisting of smectite (Hama1), smectite associated with kaolinite (Hama2), and smectite associated with illite (Hama3). However, there are also other minerals present, such as calcite, feldspar, goethite, quartz, and hematite.

4. Discussion

4.1. Macromorphological Characterization

The studied clay materials are distinguished by their color, thickness, and compactness. Field observations have led to the identification of different clay levels and their similarity across all lithological logs studied. The clay materials studied have green, gray, and yellowish colors. Green clays have a low iron content and are generally montmorillonites, illites, and smectites. Gray-colored clay materials are attributed to the complexation or chelation of organic colloids with smectite (Duchaufour, 1977). Elimbi et al., (2003) demonstrated that gray clays are bentonites from a mineralogical point of view and contain a high percentage of smectite ranging from 80% to 85%. The main impurities are quartz and feldspars, and the smectite phase is montmorillonite, which provides interesting swelling properties. Studies by Nguetnkam (2004) and Temga (2015) have shown that it is montmorillonite that adsorbs large organic cations in the interlayer spaces of clays and is responsible for the strong dark coloration of vertisols during a first hydromorphic stage where substances are adsorbed by clay and a second drying stage during which the organic matter, not protected by its bond with the clay, is almost completely destroyed under aerobic conditions (Temga et al., 2015, Njopwouo & Wandji, 1985, Djordjevic et al., 2012).

4.2. Physicochemical Characteristics

Among the most significant physicochemical characteristics are pH, exchangeable bases, and cation exchange capacity. The analyzed clay materials have a pH ranging from 7.6 to 8.5, indicating moderately basic to basic soils. Such pH and organic matter values are generally mentioned in vertisols formed on alluvial materials in the tropical zone (Nguetnkam, 2004; Azinwi et al., 2011; Djoufac et al., 2007; Temga et al., 2015). The exchangeable calcium content (Ca2+) of the clay materials studied is generally high, ranging from 10.60 to 37 meq/100g. Exchangeable calcium (Ca2+) is a flocculant agent that provides some stability to clays (Oades, 1984; Six et al., 2004). Ca2+ plays almost the same role as organic matter, but it depends much more on the original material (Igwe, 2004). The exchangeable sodium content (Na+) obtained from the clay materials ranges from low (0.17 meq/100g) to high (0.80 meq/100g). Lopez and Zinck (1991) and Igwe (2004) have shown that even in very low percentages, Na+ can play an important role in particle dispersion because it is a dispersing agent. The sum of exchangeable bases is high (17.09 meq/100g) to very high (53.45 meq/100g). These values show that these clay materials are rich in exchangeable bases (Memento de l'agronome, 1991). The cation exchange capacity (CEC) is strong to very strong, ranging from 35.60 meq/100g to 62.32 meq/100g. This can be related to the abundance of clay and the dominant clay mineral type, such as smectites associated with a certain amount of kaolinite. In some cases, smectites are known as clay minerals that have a high CEC (Nguetnkam, 2004; Driese et al., 2005; Djoufac et al., 2007; Azinwi et al., 2011; Azinwi, 2012). The saturation rate varies from moderate 37% to high 89%. These values show that the clay levels in the site of Ourokessoum in the Hamakoussou sedimentary basin are moderately to highly saturated (Memento de l'agronome, 1991).

4.3. Mineralogical Characterization

The mineralogical composition, determined by X-ray diffraction, is mainly composed of smectite associated with kaolinite, illite, and accessory minerals such as calcite, feldspar, quartz, hematite, and goethite. A similar mineral assemblage was observed on Meiganga clay materials (Sam-Tunsa et al., 2022; Mache et al., 2013, in Sagba smectite clays). This composition is generally common in vertisols (Nguetnkam, 2004; Azinwi, 2005; Djoufac et al., 2007; Azinwi et al., 2011; Kamgang et al., 2011; Azinwi, 2012). The abundance of smectite in all clay materials confirms the process of smectite formation, which requires environmental conditions such as flat areas, poorly drained environments, and contrasting climates, and results either from the crystal chemical transformation of micaceous minerals or from neoformation from ions released by hydrolysis (Pialy et al., 2009; Bocquier, 1973; Duchaufour, 1977; Segad et al., 2010). All these conditions are observed in the study area. The presence of hematite is characteristic of non-hydromorphic environments because hematite is unstable in aquatic environments and tends to transform into goethite (Voicu et al., 1996; Ngon, 2007). The combination of these climatic, environmental and topographical factors leads to the relative concentration of bases and silica with chemical analysis (SiO_2 >60%, sum of bases ~7%), and creates favorable conditions for smectite genesis. SiO_2/Al_2O_3 is >3%, confirming the presence of smectites (Nguetnkam et al., 2008).

The presence of goethite, even in small amounts, can reflect a detrital origin (Lajoie & Chagnon, 1973). The presence of feldspar, on the other hand, is of remarkable ceramic interest (Abdelhak et al., 2007). The mineral paragenesis of kaolinite associated with illite, quartz, and feldspar in the clay materials of Hamakoussou is similar to those of clay categorized as "ordinary" and commonly used in brick-making. These clays are also comparable to the mineralogical composition of sedimentary clays from Uganda (Nyaikairu et al., 2001) used for the production of fired clay bricks, as well as clays from Morocco, specifically from the Ourika Valley (Hajjaji et al., 2002) and the city of Safi. The absence of chlorite detected in the samples by XRD in the studied clay materials is consistent with that obtained by (Temga et al., 2015), but differs from that obtained in alluvial clays of the Gangetic plain in India (Bhatnagar & Goel, 2002), Tunisian clays (Jeridi et al., 2008), and Spain. This would explain why chlorite is only formed in cold zones under the influence of the physical alteration of ferromagnesian rock. The presence of illite in these materials would be due to significant terrigenous input at river mouths, resulting from the crystallographic process of bisialitization. The presence of kaolinite in this zone, where drainage is relatively low, is due to the fact that the hydrolysis of illite by potassium expulsion leads to the formation of kaolinite (Pialy et al., 2009; Brabant, 1967), and on the other hand, the alteration of feldspar leads to the formation of kaolinite (Violette, 2010). The low intensity of the kaolinite peaks in some clay layers could explain that the alteration is low. The ubiquity of quartz in clay materials is due to geological formation processes. Illite and smectite improve the plasticity of pastes (Abdelhak et al., 2007). Finally, the presence of calcite in smectite-rich clay materials indicates that the clay materials of the Hamakoussou sedimentary basin are in accordance with the work of Bentahar (2017) showing that these types of smectite have a better yield for molding sand for the foundry industry. Calcium smectites, unlike sodium smectites, increase their specific surfaces very little in the presence of water unless activated. This property makes them particularly attractive for use in the pharmaceutical industry. The same observations were made by Tsozué et al. (2017) illustrating the same mineralogical procession.

5. Conclusion

The aim of this study was to provide scientific value on the sedimentary basin of Hamakoussou from a macromorphological, physicochemical, and mineralogical perspective for the characterization of clay layers. To achieve this goal, the study was conducted in several stages, both in the field and in the laboratory. The results revealed that:

1) The macromorphology showed that the texture of the studied materials is clayey and clastic, and the boundaries between the layers are clear to gradual. Non-clay layers have a sandy-clay texture with a particulate structure. Eight (08) clay layer samples were collected and distinguished by their greenish, grayish, and sometimes yellowish coloration.

2) The physicochemistry showed that the clay layers have an alkaline pH ranging from 7.6 to 8.5. The sum of exchangeable bases is very good (17.09 mEq/100g) to exceptional (53.45 mEq/100g). The CEC is high (35.6 mEq/100g) to very high (62.32 mEq/100g). The saturation rate is high at around 87%. The Ca/Mg ionic ratio < 3 is normal to optimal, Mg/K (3 to 25) is normal to too high, and (CaMg)/K (21 to 50) is normal to too high.

3) The mineralogy revealed an abundance of smectite in all analyzed samples. The presence of other primary minerals (quartz, hematite, goethite, feldspar) resulted from the alteration of pre-existing materials and secondary minerals (calcite, kaolinite, illite) produced by neoformation. The presence of these minerals such as smectites and illite allows us to assert that these clay materials have a tendency to swell and therefore can be used for industrial exploitation. Thus, the clay materials from the sedimentary basin of Hamakoussou possess appropriate mineralogical characteristics and economic potential. However, it would be important to extend the same analyses to the rest of the basin, in order to be able to valorize and recommend the industrial exploitation of these clay materials from the Hamakoussou sedimentary basin. This information will be crucial in assessing their potential suitability as raw materials for various engineering applications, and will also help to enhance the value of these materials.

Conflicts of Interest

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

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