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Diagenetic and Geochemical Study of Sediments from the Cretaceous Basin of Babouri-Figuil (North-Cameroon)

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Abstract

The purpose of this work is to characterize the sediments of the Babouri-Figuil Basin from a diagenetic point of view, the protolith context and weathering conditions, using major element geochemistry and mineralogy of the sedimentary rocks. Microscopic observations of diagenetic phenomena (on and around detrital grains of the basin), and the study of precipitation of the cement show that these sediments have undergone phenomena of compaction, dissolution, recrystallization and cementation. Cementation of quartz by silica is controlled by the rate of precipitation of silica, which is closely related to temperature than pressure. Thus, the sediments of the basin could be influenced by hydrothermalism during diagenesis, which would have inhibited their reservoir quality by generalized cementation phenomena. Geochemical features of the sediments show high contents in SiO_2 (47.49 wt% - 90.79 wt%), Al_2O_3 (2.92 wt% - 23.18 wt%), Fe_2O_3 (0.2 wt% - 6.22 wt%) and alkali and alkaline earth metals (>3%). The chemical alteration index varies between 30.92% and 95.08%. This variation in the CIA values reflects the variation in the proportion of feldspars and different clay minerals in these sediments. However, the ICV calculation and the ICV versus CIA show compositional immature to mature sediments, with low to intense weathering character of these sediments. Petrographic and geochemical characteristics of sediments of the basin are compatible with the composition of the granitic and gneissic surrounding bedrocks.

Keywords

Diagenesis, Geochemistry, Cretaceous Sediments, Babouri-Figuil Basin, Sedimentary Basin

1. Introduction

The exploitation of sedimentary basins has prompted research into a wide range of diagenetic processes that modify the volume and distribution of sediments. The characteristics of sediments in depressed areas or accumulation basins are influenced by several components, including the diagenetic history of sediments and their geochemistry [1] [2] [3]. The main factors in the evolution of a basin are diagenetic sedimentary controls, mineralogy, geodynamic context, emplacement conditions and the nature of sediments, linked or not, to the structural evolution of the basins [4] [5].

The Babouri-Figuil Basin is one of the intracontinental basins of the Cretaceous age in North Cameroon. It belongs to the great Benue Trough which is associated with the opening of the South Atlantic. The geological sketch map of this basin highlights a fluvial type facies at the base which uses more or less strong transportation energy, and a fluvial-lacustrine type facies at the top [6]. It contains about 3000 metres of sediments with a well-known age. These sediments underwent physical-biochemical modifications after deposition, under "low" pressure and temperature conditions which prevailed in the sub-surface environment. The objective of the work is to address the diagenetic problems in this basin, in order to appreciate the evolution of the sediments under the phenomena of compaction, cementation, dissolution, and recrystallization, as well as their level of alteration. Also, an in-depth geochemical study will be done to coin the chemical composition of the sedimentary rocks in order to trace the source of the sediments of the Babouri-Figuil Basin.

2. Geological Setting

Geological work carried out in the sedimentary Basin of Babouri-Figuil in northern Cameroon has made it possible to identify Precambrian formations, represented by a basic complex of crystallophyllian rocks, and eruptive formations indicated by more or less deformed granitic intrusions. The map extract of East Garoua (**Figure 1**) highlights three types of formations in North Cameroon: surface formations, metamorphic formations and eruptive formations. The hydrological studies of North Cameroon, highlight characteristic aspects not only of the crystalline basement of this region, and the sedimentary basins of the Benue, Mayo Oulo-Léré and Babouri-Figuil rivers, particularly with respect to lithology, stratigraphy, tectonics, paleontology, sedimentology and climatology.

A geological synthesis of recent studies of the Precambrian basement of North Cameroon [7] [8] [9] and the Pan-African chain identified five lithological units. The shale unit: it consists of the epi-metamorphites of the Poli series and their equivalents [9]. This unit is composed of metabasalts and metarhyolites interlayered

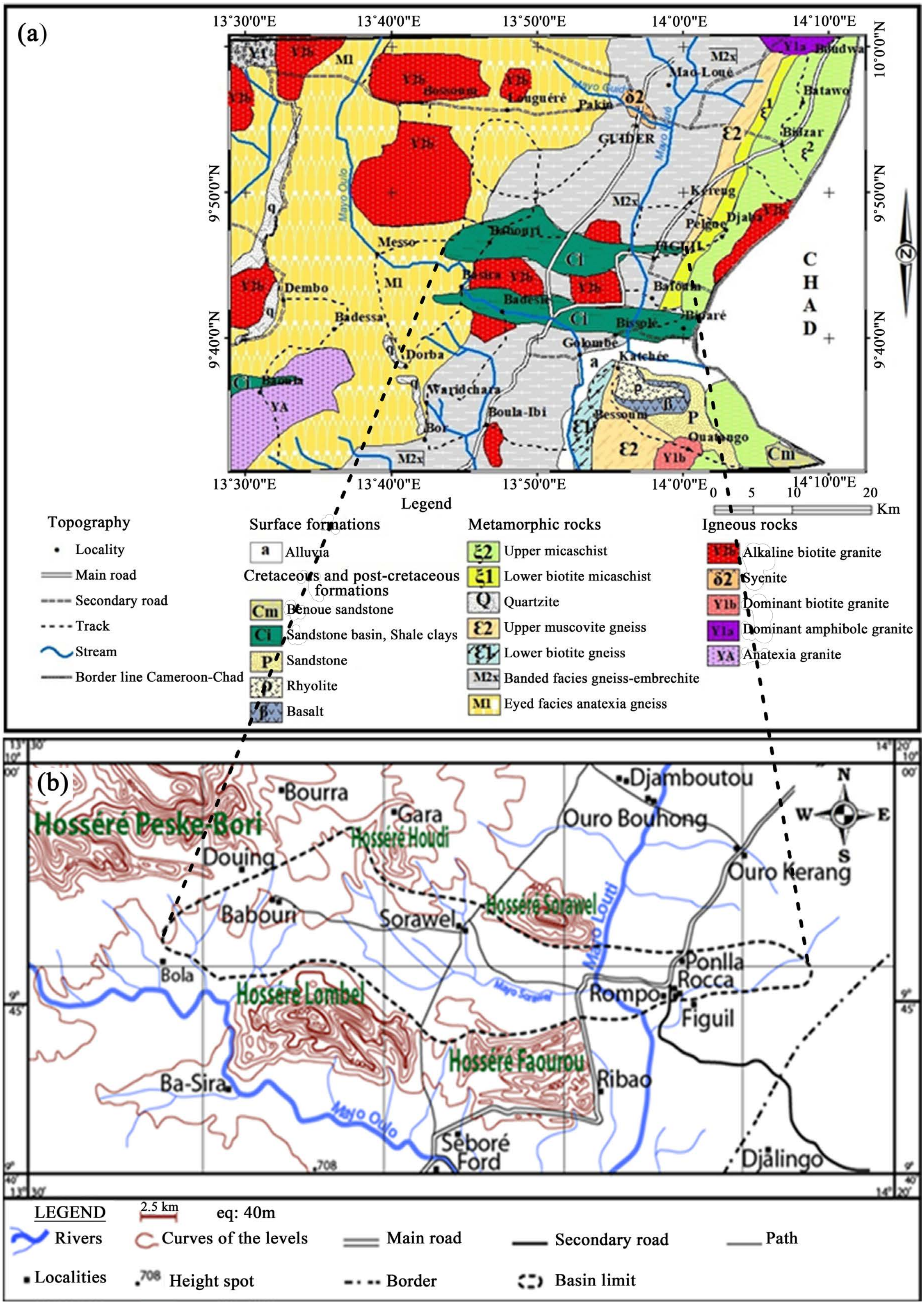

Figure 1. Geological map: (a) Excerpt from the geological map of the Cameroon (East-Garoua); (b) location map of the study area [12].

in a volcano-sedimentary sequence. The gneiss unit: this is a set of two concordant units (metagrauwackes and amphibolites) which are distinguished only by their degree of metamorphism [10]. The syn to late-tectonic granitoids D1: they correspond to the BIP (Basic to Intermediate Plutons) described by Toteu *et al.* [11]. They occur in shales and gneisses, and often contain enclaves of amphibolites. The syn to post-tectonic D2 granitoid unit: it consists mainly of pan-African plutonic rocks of the Northern Cameroon domain. The crustal origin of these rocks is multidimensional.

Late granitoid to post-tectonic D2 unit: it is a set of leucocratic granites and syenites with variable textures, which outcrop in the form of domes or inselbergs intersecting the D2 regional structure.

3. Materials and Methods

Sampling was globally done on fine-grained rocks (schistous marls and fine sandstones), which are very abundant in this basin. Within the framework of this study, about twenty samples have been selected in the basin following the four outcrops encountered, namely: Mayo Tafal (MT), with 7 samples (MT1-7); Mayo Louti (ML), where 5 samples were selected (ML1-5) Mayo Figuil (MF) with 4 samples (MF1-4) and Sorawel-Lombel (SL) with 3 samples selected (SL1-3). The work submitted to our study enabled us to produce about fifty thin sections from the 4 outcrops in the sedimentological and petrological laboratory of the University of Liège. These thin sections were observed under an optical microscope in LP and LPNA for diagenetic studies. Mineralogical analyses were performed on 4 samples, each per outcrop by X-ray diffraction (XRD) in Acme's laboratory in Vancouver, Canada. Geochemical analysis (including major elements) of the sediments of the Cretaceous Basin were carried out in all the selected samples in the previous laboratory, in order to trace the geochemical signature of the elements, fluids circulation, and to determine the different sources of terrigenous detrital inputs.

4. Results

4.1. Petrography

Petrographic studies through thin sections and mineralogy using XRD spectra of the Babouri-Figuil Basin sediments shows numerous contacts between grains and mineralogy which slightly vary in the four sampling areas.

4.1.1. Thin Section

The petrography of the thin sections ranges from tangential contacts, through concavo-convex contacts to longitudinal contacts. The concavo-convex contacts (**Figure 2(a)**) present hollows on their surface, which correspond to the imprints of neighboring particles. The presence of mica flakes is observed in this compaction, it is taken in a vice by punching quartz grains under the effect of pressure. These contacts result from mechanical compaction. The mechano-chemical con-

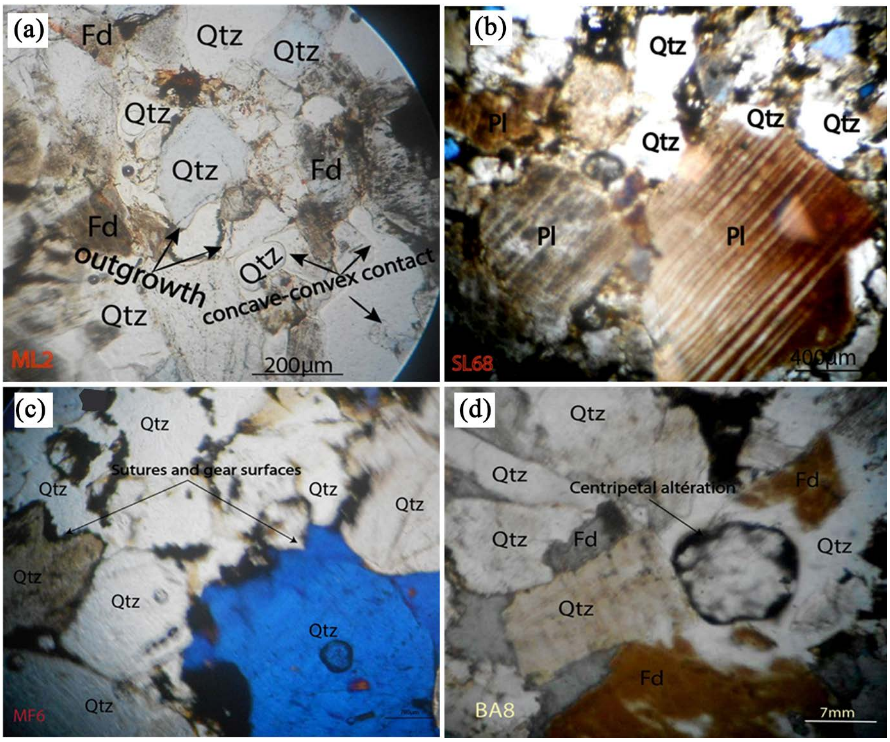

Figure 2. Different contacts between minerals in Babouri-Figuil sediments: (a) concavo-convex contact and overgrowth; (b) presence of plagioclases with planar contacts; (c) sutures and gear surfaces; (d) centrifugal alteration of miner.

tacts are also represented in the sediments of the Babouri-Figuil Basin. Dissolution surfaces are materialized by intermeshing contacts (Figure 2(c)) of irregular joints where insoluble residues accumulate. The cement in the Babouri-Figuil sandstones is observed with respect to a certain chronology, following microscopic observations: type I syntaxial cement precedes mechanical compaction, since it preserves the tangential contacts between the detrital grains; type II syntaxial cement precipitates after type I syntaxial cement and is systematically in contact with the latter.

4.1.2. XRD Mineralogy

The mineralogy of the 4 sediment samples (1 per outcrop) collected in the Babouri-Figuil Basin is dominated by silicates, carbonates, sulphates, oxides and hydroxides (Figure 3). These minerals are thought to be derived from the dismantling of the surrounding rocks on one hand, and from purely chemical processes occurring in the sediments on the other hand [12]. In the second case, they are considered as authentic minerals. The mineralogical procession is almost identical in the basin, though slight differences exist in their clay fractions. Smectite and chlorite constitute the bulk of the clay fraction in the Mayo Tafal, while kaolinite, montmorillonite, chlorite and illite constitute that of the Mayo Figuil. It is therefore very clear that kaolinite and montmorillonite are almost absent in the Mayo Tafal, and in the Mayo Figuil, it is rather smectite which is totally absent. Globally, regarding the summary on of the clay procession of schist facies in the

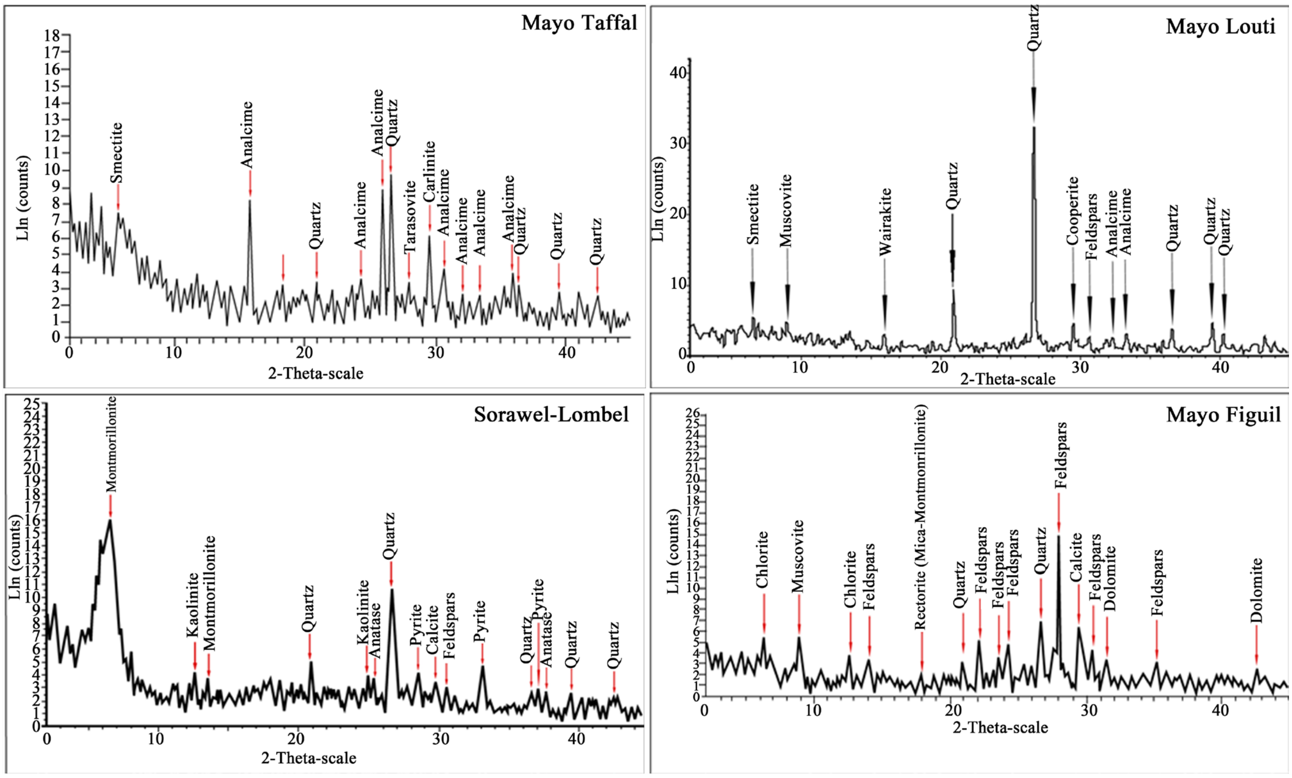

Figure 3. X-ray diffraction patterns for various samples from MT, ML, MF and SL.

Babouri-Figuil Basin [13].

It is noticed that this basin is solely composed of smectite, kaolinite and mica. The results recorded during this work reveal the presence of other clays such as montmorillonite, chlorite, illite and tarasovite, which are composite clays.

4.2. Geochemistry

Major element geochemistry enabled the characterization of the different sources of terrigenous detrital input in the Babouri-Figuil formations and to evaluate the intensity of the chemical weathering. Associated with mineralogy, this has permitted the reconstruction of the paleoconditions which prevailed during diagenesis.

Concentrations of major elements of sample sediments from the studied basin are listed in **Table 1**. The major oxides selected for the present course included SiO_2, Al_2O_3, Fe_2O_3, in **Table 1**. The major oxides selected for the present study included SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5 and MnO. These element oxides have highest concentrations in the samples located in the SL outcrop. The concentration of element oxides are: 47.49 wt% to 90.79 wt% for SiO_2 and 2.92 wt% to 23.18 wt% for Al_2O_3. Iron oxide (Fe_2O_3) is more represented in the SL outcrop sediments and varies from 0.2 wt% to 6.22 wt% in the basin. Concentrations in alkali and alkaline earth are considerably represented (>3% average) in the basin sediments. Other element oxides have concentrations < 1 wt% in almost all sediment samples from the Babouri-Figuil Basin. Major elements

Table 1. Major elements composition (wt%) and element ratios of Mayo Figuil Cretaceous sediments.

	Mayo Tafal							Mayo Louti					Sorawel-Lombel			Mayo Figuil			
	MT1	MT2	MT3	MT4	MT5	MT6	MT7	ML1	ML2	ML3	ML4	ML5	SL1	SL2	SL3	MF1	MF2	MF3	MF4
SiO_2	52.86	50.39	61.79	59.13	58.58	55.05	62.31	66.15	60.1	47.49	67.97	68.95	92.27	71.09	70.9	90.79	78.64	65.3	60.99
Al_2O_3	12.99	11.85	14.99	12.41	16.78	14.13	15.6	11.6	15.28	20.3	13.2	11.3	2.92	13.3	19.31	3.1	10.2	17.2	23.18
Fe_2O_3	4.2	1.92	2.99	2.22	3.68	2.73	3.5	1.55	3.65	4.83	1.68	5.55	1.33	2.46	6.22	0.98	0.2	2.29	3.93
MgO	1.94	0.91	1.53	1.22	0.87	1.29	0.57	2.5	1.6	3.32	1.34	3.74	0.11	0.5	0.1	0.1	0.5	2.4	4
CaO	10.21	15.04	5.04	9.4	0.02	9.95	0.02	4.8	5.8	5	4.88	3.9	0.7	0.9	0.2	0.8	4.7	0.7	2
Na_2O	5.2	5.34	6.85	6.08	0.18	7.28	0.2	3.5	5	5.23	5	1.7	0.2	1.7	0.6	0.2	0.1	0.62	1.3
K_2O	1.21	1.14	1.35	0.93	5.99	0.73	5.86	0.5	1.2	2.8	1.4	1.1	0.2	5.3	0.2	1.2	0.1	0.7	1.8
TiO_2	0.44	0.56	0.62	0.5	0.85	0.56	0.69	0.16	0.67	1.03	0.39	0.34	0.24	0.52	1.55	0.11	0.1	0.38	0.64
P_2O_5	0.14	0.17	0.17	0.15	0.09	0.19	0.07	0.14	0.15	0.23	0.25	0.1	0.1	0.1	0.1	0.27	0.22	0.35	0.48
P_2O_5	0.14	0.17	0.17	0.15	0.09	0.19	0.07	0.14	0.15	0.23	0.25	0.1	0.04	0.07	0.02	0.09	0.02	0.63	0.01
MnO	0.14	0.24	0.07	0.12	0.03	0.1	0.02	0.1	0.1	0.12	0.17	0.12	0.1	0.1	0.1	0.1	0.1	0.1	0.25
LOI	10.2	12.11	5.02	6.1	12.9	7.01	11.05	8.1	6.3	9.01	3.47	3.01	1.45	3.9	1.02	2.2	5.5	7.98	1.25
Total	99.67	99.84	100.6	98.41	100.1	99.21	99.96	99.24	100	99.59	100	99.91	99.66	99.94	100.3	99.94	100.4	98.65	99.83
K_2O/Na_2O	0.23	0.21	0.20	0.15	33.28	0.10	29.30	0.50	0.24	0.54	0.28	0.65	1.00	3.12	0.33	6.00	1.00	1.13	1.38
Fe_2O_3/K_2O	3.47	1.68	2.21	2.39	0.61	3.74	0.60	3.10	3.04	1.73	1.20	5.05	6.65	0.46	31.10	0.82	2.00	3.27	2.18
SiO_2/Al_2O_3	4.07	4.25	4.12	4.76	3.49	3.90	3.99	22.59	3.93	2.34	5.15	37.65	31.60	5.35	3.67	29.29	243.20	4.90	1.77
Al_2O_3/TiO_2	29.52	21.16	24.18	24.82	19.74	25.23	22.61	10.00	22.81	19.71	33.85	3.82	12.17	25.58	12.46	28.18	2.00	18.95	36.22
CIA	43.87	35.51	53.10	43.06	73.05	44.03	71.96	40.25	56.01	60.91	53.92	36.25	72.64	62.74	95.08	58.49	3.92	78.09	81.97
ICV	1.79	2.10	1.23	1.64	0.69	1.60	0.69	1.12	1.17	1.09	1.11	1.45	0.95	0.86	0.46	1.09	0.56	0.41	0.59

CIA (%) = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$. ICV = $(Fe_2O_3 + K_2O + Na_2O + CaO + MgO + TiO_2)/Al_2O_3$.

(Al_2O_3, Na_2O, CaO) have been correlated with silica. It appears from these correlations that the elements tend to group together on the same point. Thus, silica shows that samples belong to the same domain. Hence, it can be considered that the source of sediment input from the basin is the same. Contents in K_2O compared to Na_2O are very low except for few samples. This indicates that the sediments from the Babouri-Figuil Basin are richer in sodium than in potassium. This evidence presents the abundance of plagioclases alongside feldspars. Contents in MgO and CaO are relatively high (>3%).

In the present study, chemical weathering index (CIA) and index of compositional variability (ICV) have been calculated to determine the degree of weathering of the source area (Table 1; Figure 4). The CIA values of the sediments of Babouri-Figuil range from 30.92% to 95.08%. However, the values of ICV vary between 0.41 and 1.79. Almost all samples from SL and MF have ICV < 1, whereas almost all samples from ML and MT are >1.

5. Discussion

5.1. Diagenetic Processes

The petrographic and geochemical study of the sediments of the Babouri-Figuil

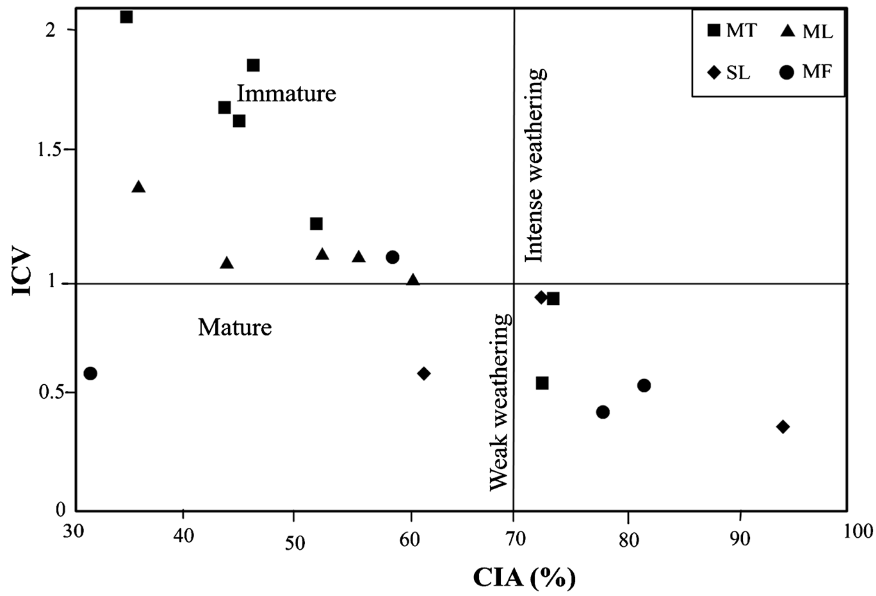

Figure 4. ICV vs. CIA diagram [26] [27] for the Cretaceous sediments from the Babouri-Figuil Basin.

Basin shows numerous contacts between grains. These types of contacts form under the effect of pressure-dissolution [14], by selective dissolution at the contact points of the particles subjected to significant stress. The formation of stylolites in these sediments is a consequence of pressure-dissolution [15]. It also accounts for the formation of overgrowths, which is a feeding phenomenon of the quartz grains (Figure 2(a) and Figure 2(c)). Thus, microstylolites and stylolites are formed in function of the size of the amplitude of the observed gear surface [16]. Mechanical-chemical compaction is marked by the reduction of the total volume of the rock. This is due to the dissolution of grains at their point of contact under the effect of stress. It is when Type I syntaxial cement is lacking that Type II syntaxial cement is in direct contact with the grains [17]. Cementing is therefore, the occlusion of the intergranular volume by precipitation of authentic minerals marked by induration and/or lithification of the sediment. It is a phenomenon observed in Babouri-Figuil sandstones with the presence of iron oxides (hematite), silica and calcite, as cement around the detrital grains.

Pressure-dissolution of the basin rocks is a deformation mechanism of the basin, and its importance is demonstrated in the compaction of the sandstones during diagenesis. The sediments (sandstones) of the basin show a dissolution of grains of low stability, namely potassium feldspars and mica, followed by the precipitation of kaolinite and/or silica leading, to the creation of secondary porosity. Corrosion dissolution of quartz grains is also observed in thin portions. The overgrowth of silica above detrital quartz grains indicates the presence of silica resulting from the dissolution of feldspars and/or quartz (Figure 2(a)). A typological duality of alteration is observed on the minerals of this basin. There is a centripetal alteration (Figure 2(d)) which would be indicative of a loss of magnesium, silicification and ferruginization of the minerals during alteration.

This could be justified by a relative accumulation of iron at the edge of the void on one hand and a centrifugal alteration, which begins from the core of the mineral [18], and makes the mineral black from the interior to the edges on the thin blades observed, on the other hand.

5.2. Protolith Context

The petrographic and geochemical characteristics of the sedimentary rocks of the Babouri-Figuil Basin indicate that the figurative elements could come from the dismantling of granitic bedrock. The ratio Al_2O_3/TiO_2 ranges from 2.00 to 36.21. This ratio is relatively high, and is associated with the geochemical classification according to Herron [19]. It reveals that the samples analyzed are mostly wacke (**Figure 5**), indicating a more continental source [20] of sediments of the Babouri-Figuil Basin. Similarly, the diagram in **Figure 6**, based on Suttner and Dutta [21], indicates that sediments form the Babouri-Figuil Basin were mostly deposited in a semi-arid and arid environment, which is justified by the presence of the hard-grounds and numerous desiccation cracks observed in the basin. They are associated with an arid environment. Also the discrimination functional diagram of the original signatures of the sandstone-mudstone suites using the following major element ratios after Roser and Korsch [22]: Discrimination function 1 = $30.638TiO_2/Al_2O_3 - 12.541Fe_2O_3(total)/Al_2O_3 + 7.329MgO/Al_2O_3 + 12.031Na_2O/Al_2O_3 + 35.402K_2O/Al_2O_3 - 6.382$; Discrimination function 2 = $56.500TiO_2/Al_2O_3 - 10.879Fe_2O_3(total)/Al_2O_3 + 30.875MgO/Al_2O_3 - 5.404Na_2O/Al_2O_3 + 11.112\ K_2O/Al_2O_3 - 3.89$. It shows that most of the sediments derived from felsic igneous rocks, quartz sedimentary rocks, mafic igneous rocks and occasionally intermediate igneous origin (**Figure 7**). This could be linked to the mineralogy of the studied sediments and the surrounding rocks made-up of leucocratic granites and syenites and occasionally the gneissic formations.

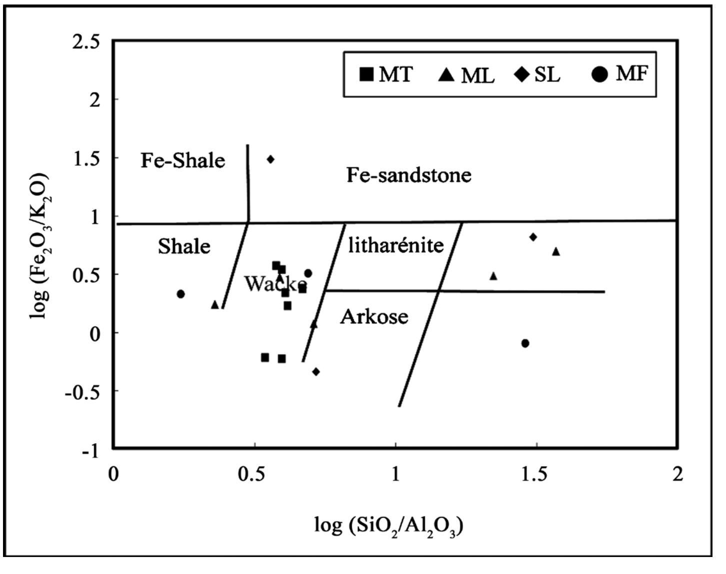

Figure 5. Geochemical classification of samples according to the $\log(SiO_2/Al_2O_3)$ - $\log(Fe_2O_3)/K_2O$ diagram [19].

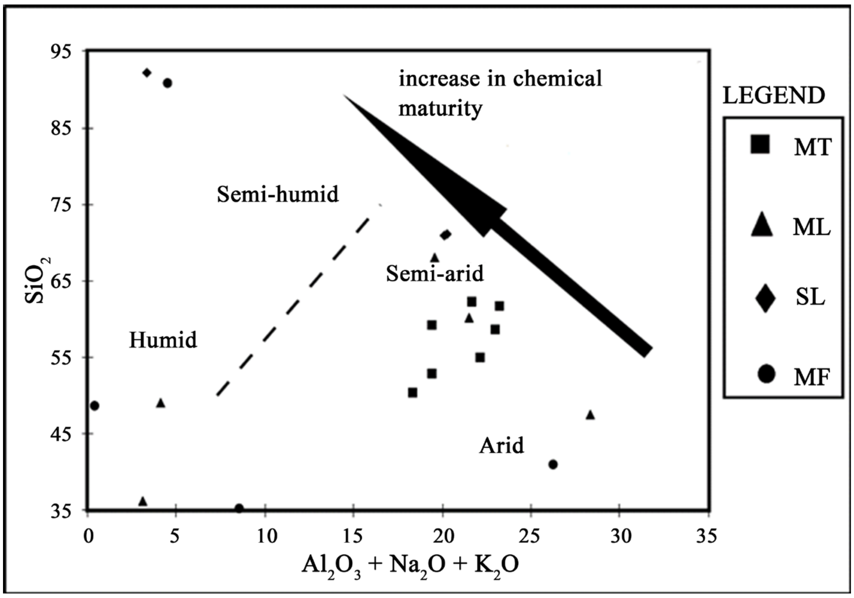

Figure 6. P_2O_5 versus Al_2O_3 in the sediments for paleoenvironmental reconstructions of Babouri-Figuil Basin [21].

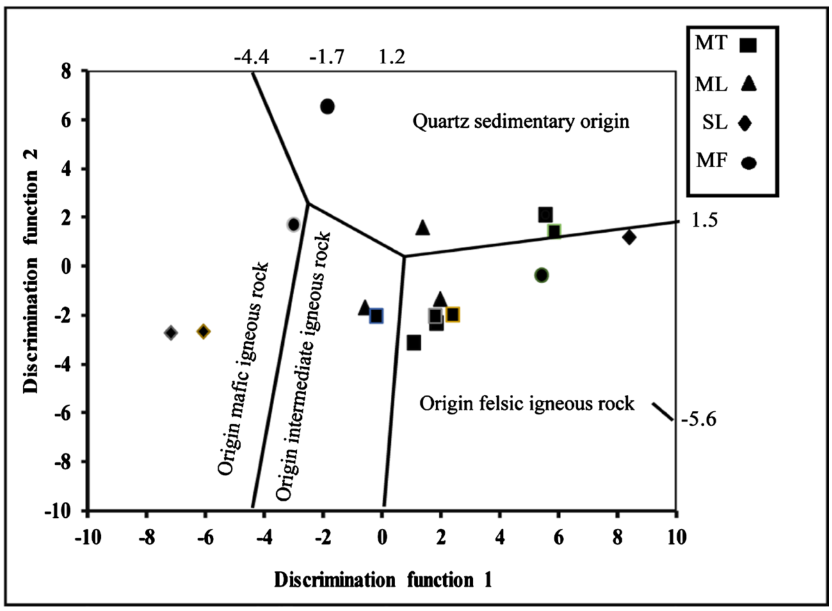

Figure 7. Discrimination functional diagram for original signatures of sandstone-mudstone suites using major element ratios [22].

5.3. Weathering Conditions and Maturity

The degree of chemical weathering of source rocks and the maturity of sediments are measured by determining the CIA, ICV, and also through the mineralogy. These indices correspond to the sum of the weathering processes that affected these materials from the sedimentation media (supergenic weathering processes) and during burial (diagenetic and/or hydrothermal weathering processes). Mineralogical features from the studied sediments revealed presence of clay minerals and high content in iron oxide coatings, which may result from diagenetic processes or from intense weathering in the source area. The presence of kaolinite and montmorillonite suggests chemical weathering of feldspars, which is the mineral phase from the granitic and gneissic source area. In the Babouri-Fifuil basin, the chemical weathering index varies between 30.92% and 95.07%. These observations indicate that the elements shown also come from the dismantling of volcanic bedrock as well as from the granitic massif. The SiO_2/Al_2O_3 ratio in the Babouri-Figuil Basin is average (22.10%). The variation in CIA values and SiO_2/Al_2O_3 reflects the variation in the proportion of feldspars and different clay minerals in these sediments [23]. It is therefore high in samples where feldspars are in low proportion or absent (SL, MF). This comparison with the low feldspar rate is the result of intense chemical alteration in the basin.

Moreover, chemical index such as CIA values are well correlated in these sediments (**Figure 4**), exhibiting low to high chemical weathering (**Table 1**). The above correlations suggest that weathering can be significantly influenced by the grains size of the sediment [24]. Variation in values of chemical indices values of the studied sediments can be attributed to the variation in the composition of source rocks. Titanium oxide (TiO_2) shows a positive correlation with Al_2O_3 (**Figure 6**) in general, and illustrates an accumulation of immobile elements. This accumulation coupled with the high CIA values indicates considerable chemical alteration of the terrigenous detrital materials [3] [25] [26]. For sediments from the Babouri-Figuil Basin, ICV > 1 suggests compositionally immature sediment and ICV < 1 suggests compositionally mature sediment [27]. From the ICV calculation and the ICV versus CIA diagram proposed by Cox *et al.* [27], almost all sediments from MT and ML are immature, and a low or weak weathering character of these sediments is confirmed. Contrarily, sediments from SL and MF are generally mature with intense weathering except for two samples (**Figure 4**).

6. Conclusion

The Babouri-Figuil Basin is the northernmost of the Cretaceous basins of northern Cameroon. According to the results of this study; based on diagenesis, geochemical and mineralogical analyses and petrographic observations, it has been proven that sediments from this basin have undergone compaction, dissolution, recrystallization and cementing phenomena. The latter is the occlusion of the intergranular volume by precipitation of authentic minerals marked by induration and/or lithification of the sediment. Compaction phenomena are of two types: mechanical compaction marked by the different contacts between minerals, and mechano-chemical compaction which is visible by the presence of microstylolites and stylolites, formed according to the magnitude of the observed gear surface area. The alteration index shows a variation in CIA values that reflects the variation in the proportion of feldspars and different clay minerals in these sediments. It also shows a low to an intense degree of weathering. The petrographic and geochemical characteristics of the sedimentary rocks of the Babouri-Figuil Basin are much more indicative of the dismantling of granitic and sometimes gneissic bedrock confirmed by the mineralogy which consists of smectite, kaolinite and mica, and other clays such as montmorillonite, chlorite, illite and tarasovite.

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Conflicts of Interest

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

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