# Geochemical Study of the In Wagar and Garadaoua Formations of the Iullemmeden Basin in South Central Niger (West Africa): Nature of the Sediments, Paleoclimatic Conditions and Paleoalteration of Source Rocks

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**Abstract:** The present study focuses on the geochemical characteristics of the Maastrichtian-Paleogene deposits of the In Wagar and Garadaoua formations in the Iullemmeden basin. The methodology used is based on the geochemical characterisation of samples. The sediments of the In Wagar and Garadaoua formations are detrital and carbonate. The study reveals that their chemical composition depends strongly on the chemical composition of the source rocks. The different ratios calculated and the diagrams drawn according to the major elements as well as the study of the fossils show a diversity of source rocks that contributed to the deposition of the sampled sediments. Interpretation of the diagrams shows that the sediments are rich in quartz and feldspars, indicating a felsic source. The fossil record indicates a warm and humid tropical climate during the deposition of the sediments.

**Key words:** Iullemmeden Basin, Maastrichtian, Paleocene-Ypresian, Geochemistry, Origin of sediments.

## 1. Introduction

The Iullemmeden Basin, with its pentagonal shape [3], is a vast intracratonic basin that extends from the southern Hoggar to the northern Benino-Nigerian Shield. The study area, the southern part of the Iullemmeden basin (Garadaoua village), contains sediments of Meso-Cenozoic age consisting of sands and silts, argillites and marlstones. It is therefore a reference basin in West Africa since numerous field and laboratory studies have been carried out such as tectonic, sedimentological, paleontological, paleoclimatic and sedimentary mineralogical studies. These studies have provided a better understanding of the geology and geochemistry of the basin. The aim of this study is to examine the chemical composition of sedimentary rocks of the In Wagar and Garadaoua formations of Maastrichtian-Paleogene age in order to determine the geochemical characteristics and probable origins of the sediments of the Iullemmeden Basin.

## 2. Geological context of the Iullemmeden basin

The Iullemmeden basin is made up of alternating marine sediments and continental deposits laid down during the various transgressive and regressive episodes that have marked its geological history.

### 2.1. Presentation of the Iullemmeden basin

The Iullemmeden Basin is bounded to the south by the Benino-Nigerian shield, to the south-west by the crystalline Liptako massif, to the north-west by the Adrar des Iforas, to the north by the Hoggar, to the north-east by the Aïr massifs and to the east by the Damagaram-Mounio (**Fig. 1**). It communicates to the northwest with the Taoudenni basin via the Gao Strait and to the east with the Eastern Niger basin via the Damergou sill [5] (**Fig. 1**).

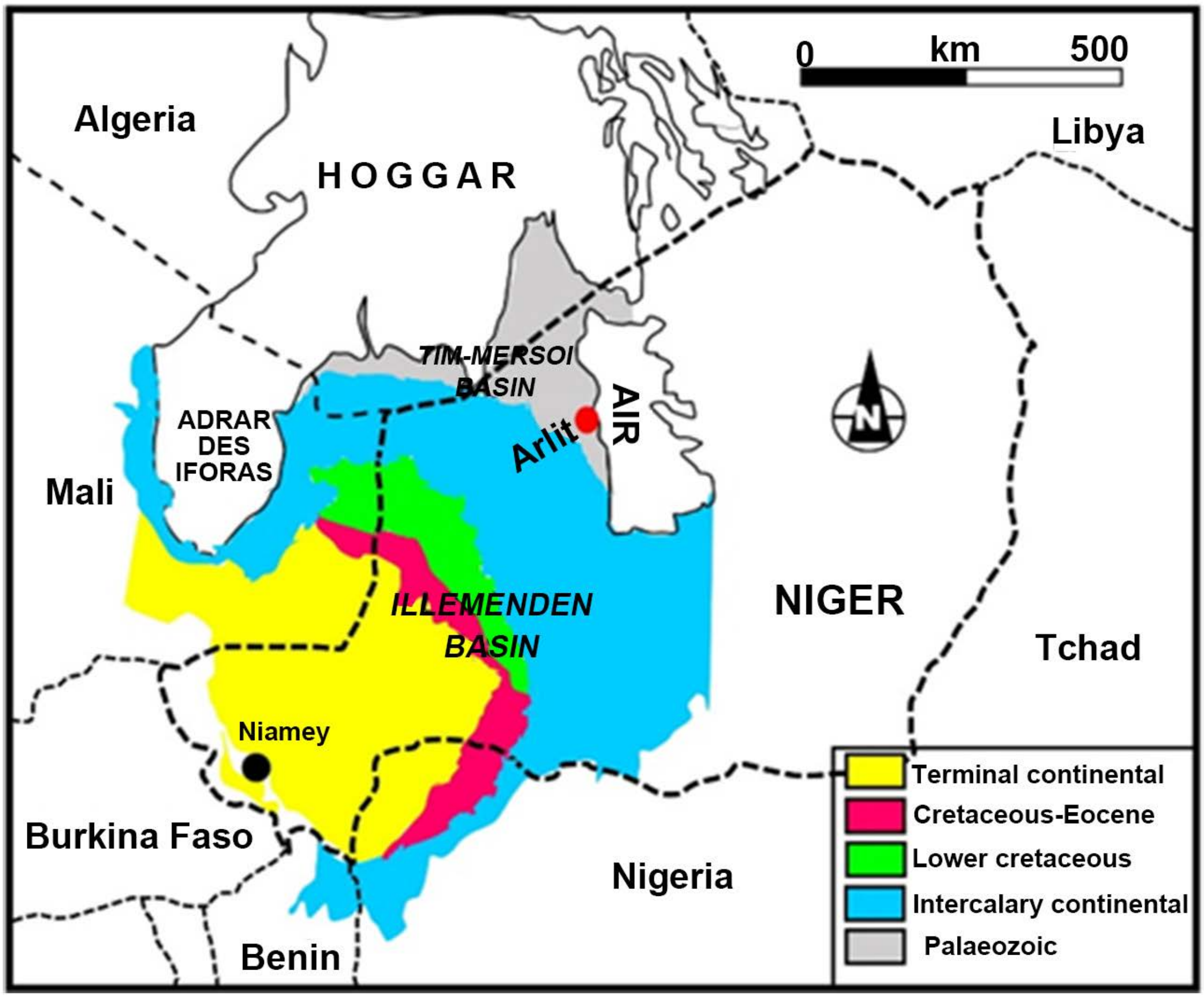
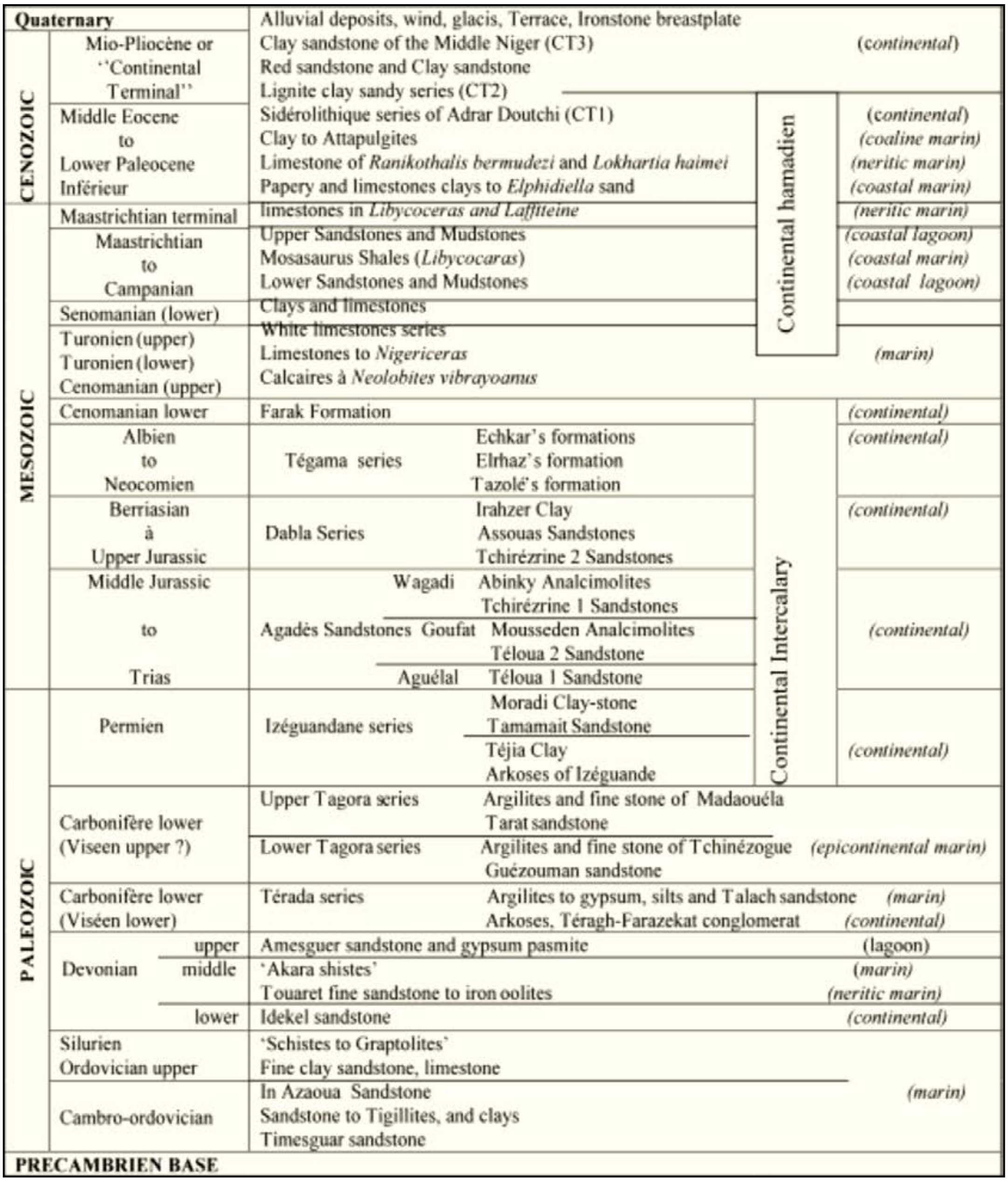


**Figure 1:** Simplified geological map of the Iullemmeden basin [4] .

## 2.2 Stratigraphic setting

The Iullemmeden basin contains sedimentary series ranging in age from Cambrian to Quaternary. **Table 1** below [1] gives a general overview of the sedimentary series of the Iullemmeden basin. The Iullemmeden Basin is an intracratonic basin that has been established in the pan-African mobile zone east of the West African Craton (**Fig. 1**). It contains Paleozoic and Meso-Cenozoic sediments. During geological times, this basin has been the site of intracratonic sedimentation resulting in a displacement of the deposit zones from northeast to south-west. Paleozoic sediments occupy the northern part of the basin, while Mesozoic and Cenozoic deposits occupy the most southwestern part of the basin.

**Table 1:** Post-Precambrian Sedimentary Formations of the Iullemmeden Basin [2].



| | | | | | | |
|---|---|---|---|---|---|---|
| **Quaternary** | | Alluvial deposits, wind, glacis, Terrace, Ironstone breastplate | | | | |
| **CENOZOIC** | Mio-Pliocène or ''Continental Terminal'' | Clay sandstone of the Middle Niger (CT3)<br>Red sandstone and Clay sandstone<br>Lignite clay sandy series (CT2) | | | | *(continental)* |
| | Middle Eocene to Lower Paleocene Inférieur | Sidérolithique series of Adrar Doutchi (CT1)<br>Clay to Attapulgites<br>Limestone of *Ranikothalis bermudezi* and *Lokhartia haimei*<br>Papery and limestones clays to *Elphidiella* sand | | | Continental hamadien | *(continental)*<br>*(coaline marin)*<br>*(neritic marin)*<br>*(coastal marin)* |
| **MESOZOIC** | Maastrichtian terminal | limestones in *Libycoceras and Laffiteine* | | | | *(neritic marin)* |
| | Maastrichtian to Campanian | Upper Sandstones and Mudstones<br>Mosasaurus Shales (*Libycocaras*)<br>Lower Sandstones and Mudstones | | | | *(coastal lagoon)*<br>*(coastal marin)*<br>*(coastal lagoon)* |
| | Senomanian (lower) | Clays and limestones | | | | |
| | Turonien (upper)<br>Turonien (lower)<br>Cenomanian (upper) | White limestones series<br>Limestones to *Nigericeras*<br>Calcaires à *Neolobites vibrayoanus* | | | | *(marin)* |
| | Cenomanian lower | Farak Formation | | | Continental Intercalary | *(continental)* |
| | Albien to Neocomien | Tégama series | | Echkar's formations<br>Elrhaz's formation<br>Tazolé's formation | | *(continental)* |
| | Berriasian à Upper Jurassic | Dabla Series | | Irahzer Clay<br>Assouas Sandstones<br>Tchirézrine 2 Sandstones | | *(continental)* |
| | Middle Jurassic to Trias | Agadès Sandstones | Wagadi | Abinky Analcimolites<br>Tchirézrine 1 Sandstones | | *(continental)* |
| | | | Goufat | Mousseden Analcimolites<br>Téloua 2 Sandstone | | |
| | | | Aguélal | Téloua 1 Sandstone | | |
| **PALEOZOIC** | Permien | Izéguandane series | | Moradi Clay-stone<br>Tamamait Sandstone | | |
| | | | | Téjia Clay<br>Arkoses of Izéguande | | *(continental)* |
| | Carbonifère lower (Viseen upper ?) | Upper Tagora series | | Argilites and fine stone of Madaouéla<br>Tarat sandstone | | |
| | | Lower Tagora series | | Argilites and fine stone of Tchinézogue<br>Guézouman sandstone | | *(epicontinental marin)* |
| | Carbonifère lower (Viséen lower) | Térada series | | Argilites to gypsum, silts and Talach sandstone | | *(marin)* |
| | | | | Arkoses, Téragh-Farazekat conglomerat | | *(continental)* |
| | Devonian upper | Amesguer sandstone and gypsum pasmite | | | | (lagoon) |
| | Devonian middle | 'Akara shistes' | | | | (*marin)* |
| | | Touaret fine sandstone to iron oolites | | | | *(neritic marin)* |
| | Devonian lower | Idekel sandstone | | | | *(continental)* |
| | Silurien<br>Ordovician upper | 'Schistes to Graptolites'<br>Fine clay sandstone, limestone | | | | *(marin)* |
| | Cambro-ordovician | In Azaoua Sandstone<br>Sandstone to Tigillites, and clays<br>Timesguar sandstone | | | | |
| **PRECAMBRIEN BASE** | | | | | | |

## 3. Methodological Approach and Materials

This geochemical study was carried out at the Garadaoua outcrop, as it contains the two formations studied (In Wagar and Garadaoua). The geochemical assays of major elements were carried out at the MCC (Malbaza Cement Company) laboratory. First, the geochemical profiles obtained from the Excel software were synchronised with the sedimentological section of the outcrop using the Canvas 11 software. Subsequently, the ratios between the elements were calculated to study their vertical variation. An inter-element correlation was used to calculate the correlation coefficient in order to confirm the main trends observed in the geochemical profiles.

To find out the geochemical classification of the sedimentary rocks, the maturity of the sediments, the provenance of the sediments, the palaeoalteration and the palaeoclimate, several diagrams were designed using IBM SPSS Statistics 20 software. These are the [6], [7], [8] and [9] diagrams respectively.

## 4. Results and discussion

### 4.1. Variation in the content of major elements

The results of the geochemical determination of the major elements ($SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, MgO, $Na_2O$ and $K_2O$) (**Table 2**) of the samples taken at Garadaoua show a high $SiO_2$ content ranging from 20 w.% to 92 w.%. This high $SiO_2$ content reflects a quartz enrichment of the samples studied, according to the criteria of [25], which can be traced back to the samples from the silt-clay-gravel formation of In Wagar. The high $SiO_2$ and relatively high $Al_2O_3$ contents, ranging from 0.2 w.% to 5 w.%, characterise a felsic origin of the sediments. The high CaO values, ranging from 0.5 w.% to 43 w.%, confirm the carbonate nature of some samples, particularly those from the Garadaoua formation. The high iron content of between 0.5 w.% and 17 w.% was related to the sandstone-clay-iron level of the In Wagar formation. The high MgO values of 0.5 w.% to 5 w.% reflect an enrichment in dolomite in certain levels such as the papyrus shales. Very low $Na_2O$ values ranging from 0.5 w.% to 1 w.% and $K_2O$ values ranging from 0.02 w.% to 0.5 w.% should be noted. The very low $Na_2O$ and $K_2O$ contents, all below 1 w.%, reveal a significant $K_2O/Na_2O$ ratio >1. The latter corresponds to the potassic character which is a reliable parameter for assessing the nature of the source rocks. The high value of the $K_2O/Na_2O$ ratio (greater than 1) indicates the presence of potassium feldspar (K-feldspars) in the Garadaoua sediments.

The general appearance of the geochemical profiles (**Fig. 2**) and the comparison with the lithology make it possible to distinguish between elements related to limestones and elements accompanying the argillites (or marls).

**Table 2:** Chemical analyses of major elements in the Garadaoua sector.

| Colonne1 | SiO2 % | Al2O3 % | Fe2O3 % | MgO % | Na2O% | K2O% | CaO % | perte au feu |
|---|---|---|---|---|---|---|---|---|
| **GD 18** | 51,09 | 1,87 | 5 | 3,99 | 0,36 | 0,04 | 2,08 | 35,57 |
| **GD 17** | 28,18 | 0,93 | 2 | 3,1 | 0,26 | 0,06 | 32,04 | 33,43 |
| **GD 16** | 52,57 | 4,42 | 6,6 | 4,62 | 0,24 | 0,15 | 2,04 | 29,36 |
| **GD 15** | 31,98 | 0,26 | 0,6 | 2,1 | 0,21 | 0,8 | 40,22 | 23,83 |
| **GD 14** | 34,51 | 0,67 | 0,8 | 1,23 | 0,18 | 0,7 | 42,64 | 19,27 |
| **GD 13** | 37,06 | 0,67 | 0,4 | 0,76 | 0,22 | 0,43 | 39,08 | 21,38 |
| **GD 12** | 46,8 | 1,74 | 3,8 | 4,21 | 0,22 | 0,41 | 7,74 | 35,08 |
| **GD 11** | 43,08 | 1,6 | 1,7 | 3,83 | 0,19 | 0,4 | 1,62 | 47,58 |
| **GD 10** | 87,8 | 1,07 | 3,4 | 2,66 | 0,24 | 0,22 | 1,88 | 2,73 |
| **GD 9** | 92,92 | 0,35 | 1,16 | 1,09 | 0,09 | 0,18 | 1,98 | 2,23 |
| **GD 8** | 73,1 | 0,2 | 16,4 | 1,5 | 0,22 | 0,15 | 1,96 | 6,47 |
| **GD 7** | 51,99 | 2,4 | 30 | 2,12 | 0,13 | 0,19 | 0,82 | 12,35 |
| **GD 6** | 83,12 | 1,34 | 5 | 0,92 | 0,3 | 0,13 | 8,94 | 0,25 |
| **GD 5** | 60,02 | 0,4 | 16 | 0,81 | 0,19 | 0,8 | 0,7 | 21,08 |
| **GD 4** | 20,05 | 3,74 | 36,2 | 1,02 | 0,21 | 0,42 | 5,76 | 32,6 |
| **GD 3** | 46,86 | 0,66 | 5,6 | 3,6 | 0,22 | 0,26 | 5,2 | 37,6 |
| **GD 2** | 92,38 | 1,34 | 3,2 | 0,71 | 0,09 | 0,02 | 0,8 | 1,46 |
| **GD 1** | 90 | 2 | 3,5 | 0,22 | 0,12 | 0,05 | 1,38 | 2,73 |

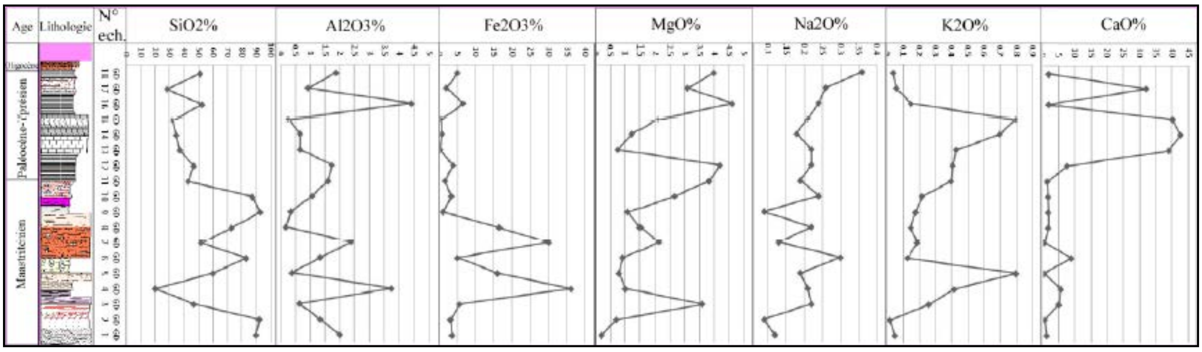


**Figure 2:** Variation in major element contents in the Garadaoua sector**.**

### 4.2 Inter-element correlation

To confirm the trends observed in the geochemical profile, correlations between the elements were established. These are mainly correlations between $Al_2O_3$ and $SiO_2$; $Fe_2O_3$ and $SiO_2$; MgO and $SiO_2$; $Na_2O$ and $SiO_2$; $K_2O$ and $Al_2O_3$; CaO and $SiO_2$.

The diagrams $Al_2O_3$ vs. $SiO_2$ (**Fig. 3 A**), $Fe_2O_3$ vs. $SiO_2$ (**Fig. 3 B**), MgO vs. $SiO_2$ (**Fig. 3 C**), $Na_2O$ vs. $SiO_2$ (**Fig. 3 D**), $K_2O$ vs. $Al_2O_3$ (**Fig. 3 E**), CaO vs. $SiO_2$ (**Fig. 3 F**) show the relationships between the major elements.

The values of $SiO_2$ in relation to the other elements ($Al_2O_3$, $Fe_2O_3$, MgO, $Na_2O$, $K_2O$ and CaO) indicate a medium correlation with a correlation coefficient R ranging from 0 w.% to 0.5 w.%. These results suggest that the Garadaoua sediments are sandstone in nature.

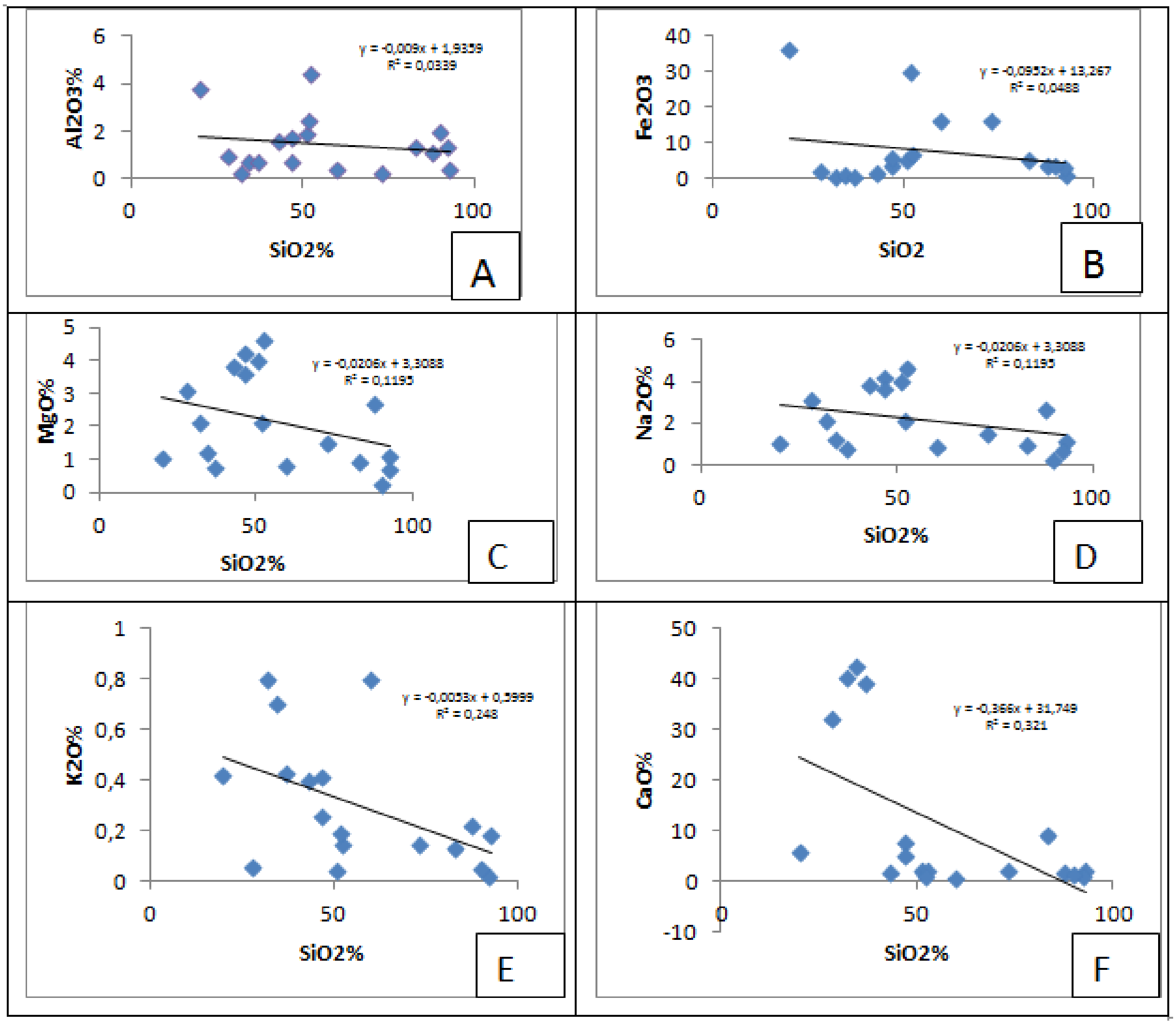


**Figure 3:** Correlation diagrams between SiO2 and other major elements ($Al_2O_3$ vs $SiO_2$ (A), $Fe_2O_3$ vs $SiO_2$ (B), MgO vs $SiO_2$ (C), $Na_2O$ vs $SiO_2$ (D), $K_2O$ vs $Al_2O_3$ (E), CaO vs $SiO_2$ (F)).

## 5. Geochemical classification of Garadaoua sediments

### 5.1. Nature of the sediments

To determine the geochemical nature of the Garadaoua sediments, the samples were projected into the [6] diagram. Based on the concentration of major elements, we used this terrigenous sediment classification diagram (log ($Na_2O/K_2O$) versus log ($SiO_2/Al_2O_3$)) (**Fig. 4**), to determine the nature of the sampled rocks. The samples projected in the Herron (1988) diagram are found in the fields corresponding to ferruginous sandstones, quartz arenites and subarkoses (**Fig.4**). This result reflects the diversity of source rocks that contributed to the deposition of the sediments sampled in the study area. This enrichment in quartz and feldspars reflects a source of felsic input.

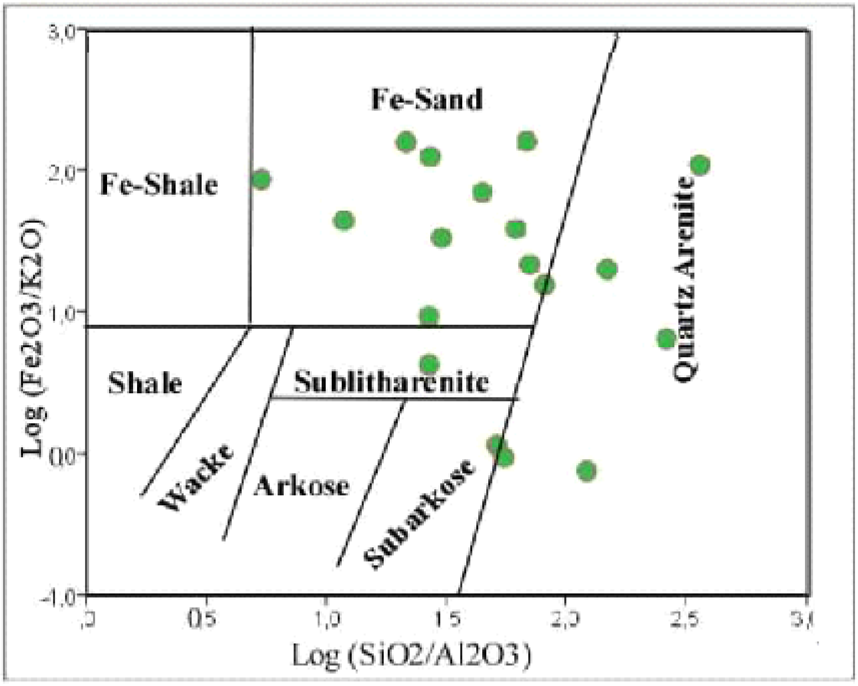


**Figure 4:** Classification diagram of the sedimentary rocks of Garadaoua [6].

### 5.2. Determination of chemical maturity of sediments

Classifications based on the quartz-feldspar-lithic fragment assemblage can be used to distinguish the mature from immature sediments. The geochemical characters most commonly used to determine the chemical maturity of sediments are the $SiO_2$ content and the $SiO_2/Al_2O_3$ ratio [10]. $SiO_2/Al_2O_3$ ratio values greater than 1 indicate a high chemical maturity of the samples examined. On the other hand, low values of the $Al_2O_3/SiO_2$ ratio below 1, confirm the quartz enrichment of the studied samples.

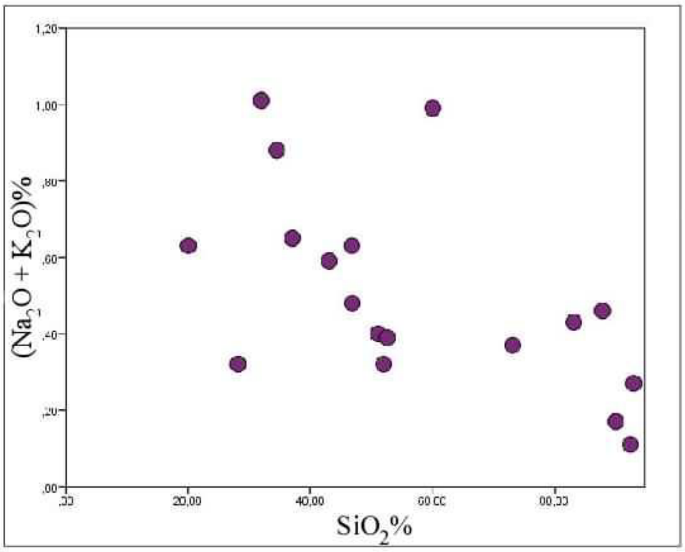


**Figure 5:** Na2O versus SiO2 diagram showing the maturity of the sedimentary material of the Garadaoua sediments [7] .

In the $SiO_2$ versus $Na_2O+K_2O$ diagram (**Fig. 5**) the elements show no correlation with $SiO_2$ (**Fig. 5**). This reflects the maturity of the sedimentary material. [7] uses the ($Na_2O$ + CaO) versus $SiO_2$ diagram to assess the potassic character of sedimentary rocks. According to this diagram, the studied samples show an insignificant potassic character which could reflect a mafic source (**Fig. 6**).

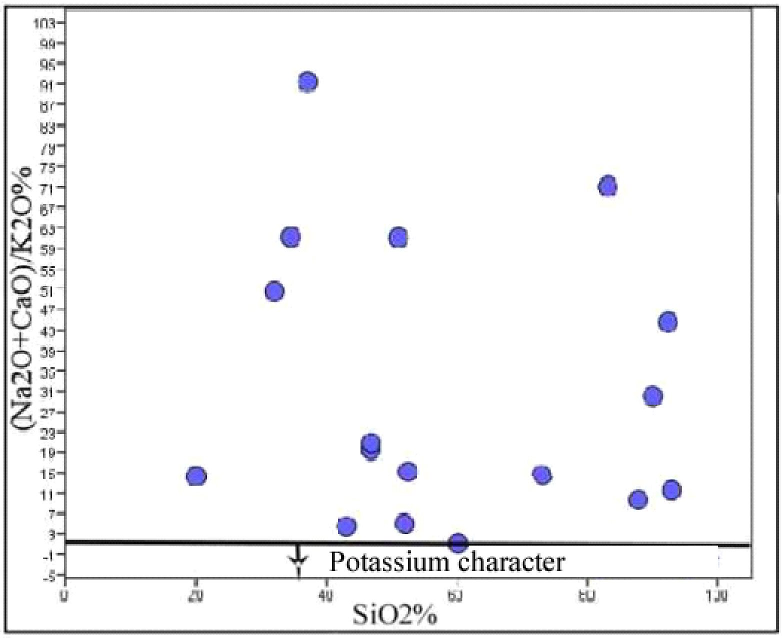


**Figure 6:** Diagram $(Na_2O+CaO)/K_2O$ versus SiO2, showing the potassium character of the sedimentary material.

### 5.3. Paleoclimatic conditions

The diagram of [9] was adopted to determine the palaeoenvironment of deposition of the sediments of the In Wagar and Garadaoua formations of the Iullemmeden basin.

The projection of the major element contents of the different samples of the Garadaoua sedimentological section define humid climates (**Fig. 6**). The study of the microfauna and microflora of the In Wagar (Maastrichtian) and Garadaoua (Palaeocene-Ypresian) formations indicates a hot and humid tropical climate. The ferruginous, phosphate and silicified nature of the In Wagar Formation is consistent with the hot and humid tropical climate that prevailed during the Maastrichtian period. Similar phenomena (ferruginisation and phosphatisation) have been reported in Senegal by [11]. They result from a lithodependent alteration under a hot and humid tropical climate, after emersion of the sediments.

The clayey procession of the Garadaoua Formation, dominated by clay minerals such as muscovite, smectites and kaolinite [12], characterises a hot and humid climate with contrasting seasons. These indications are in agreement with the conclusions of [13] who envisages, thanks to pollens, a tropical to intertropical climate in the Paleocene in the Iullemmeden basin.

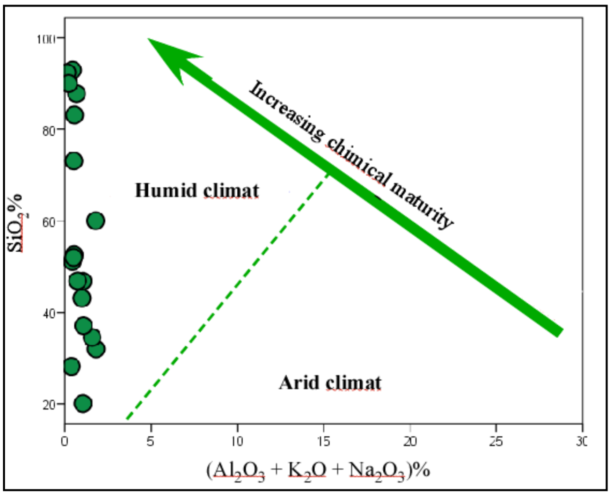


**Figure 7:** Climate characterisation of the depositional environment of the sediments of the In Wagar and Garadaoua formations, deduced from the samples projected in the diagram of [9].

### 5.4. Paleoalteration of source rocks

The chemical composition of sedimentary rocks is strongly dependent on the chemical composition of the source rocks [26], [14;15], [16], [17], [18], [19]. Three indices were used to infer the nature and degree of weathering of the source rocks that contributed to the filling of the Iullemmeden basin. These are the Chemical Index of Alteration (CIA), the Plagioclase Index of Alteration (PIA) and the Chemical Index of Weathering (CIW).

Healthy rocks generally have a CIW of 50 w.% to 60 w.% [18]. The degree of chemical weathering results in a higher CIA, mainly due to the production of clay minerals. It produces AIC values of 85 w.% to 100 w.% . This index uses molar proportions, following the formula CIA = [Al2O3 / (Al2O3 + CaO + $K_2O$ + $Na_2O$)] x 100 [20].

A selection of eighteen samples from the In Wagar and Garadaoua formations gives AIC values between 0 and 70 with an average of 35. These AIC values do not indicate an intense degree of chemical alteration during the sedimentary process at the origin of the rocks studied. This low degree of chemical alteration for our samples could mean a high rate of erosion and rapid deposition of the sediments.

It should be noted that AIC values close to 50 w.% for healthy feldspars vary from 70-75 w.% for the average clay [21], [22], reflecting the composition of phyllite silicates such as illites, muscovite and smectites as weathering minerals. Intense weathering can provide indices up to values close to 100 w.% corresponding to kaolinite, chlorite and gibbsite type minerals. In Figure 8 D, all the points representative of the composition of the rocks studied are positioned along a range more or less parallel to the $Al_2O_3$ -CN axis, up to the intersection of the $Al_2O_3$-$K_2O$ axis in the vicinity of the points corresponding to the respective theoretical composition of feldspars and micas (muscovite).

In the A-CN-K diagram of [8] (**Fig. 8 D**) reflects the alteration of source rocks favouring the formation of clay minerals such as muscovite ($KAl_2[Si_3AlO_{10}$ (OH, F$)_2$], illite ($K_xAl_2[Si_{4-x}AlxO_{10}](OH)_2$) and kaolinite ($Al_4[Si_4O_{10}](OH)_8$) from feldspars such as plagioclase and orthoclase: K[Si3AlO8]. This mineral paragenesis explains the alteration of granite, which depends essentially on the alteration of potassium feldspar (orthoclase). The fine structure of these minerals, which are often very heterogeneous (numerous fluid or solid inclusions), makes them easy to alter under the action of fluids rich in F-, OH-, Cl-, linked to the end of the crystallisation of magmas or to hydrothermalism. Once placed in surface conditions, granitic rocks in contact with the hydrosphere are easily altered. At low to medium alteration conditions, potassium feldspar alters to muscovite in the form of small flakes (sericite or damourite) by serialisation or damourisation. The hydrolysis of sericite leads to the loss of potassium, which results in the appearance of the mineral Illite. The latter, under high alteration conditions, loses potassium and is transformed into kaolinite (kaolinitisation) (**Fig. 8 D**).

In **Fig. 8 D**, the trend line of the points intersects the Plagioclase-Potassium Feldspar (Plg-Fk) axis at the point where the Plg-Fk ratio is about 70 w.%, indicating a probable provenance from the felsic rocks. The low to medium alteration conditions reflect a serialisation of the orthoclase to muscovite. The AIC value ranging from 0 w.% to 70 w.% indicates that the source rocks of the Garadaoua sector sediments were subjected to moderately altering conditions. These conditions are characterised: (1) either by a relief, initially more or less steep, which favoured mechanical rather than chemical alteration, but which subsequently evolved towards a relief with gentle slopes, (2) or by a climate with low temperature and high humidity.

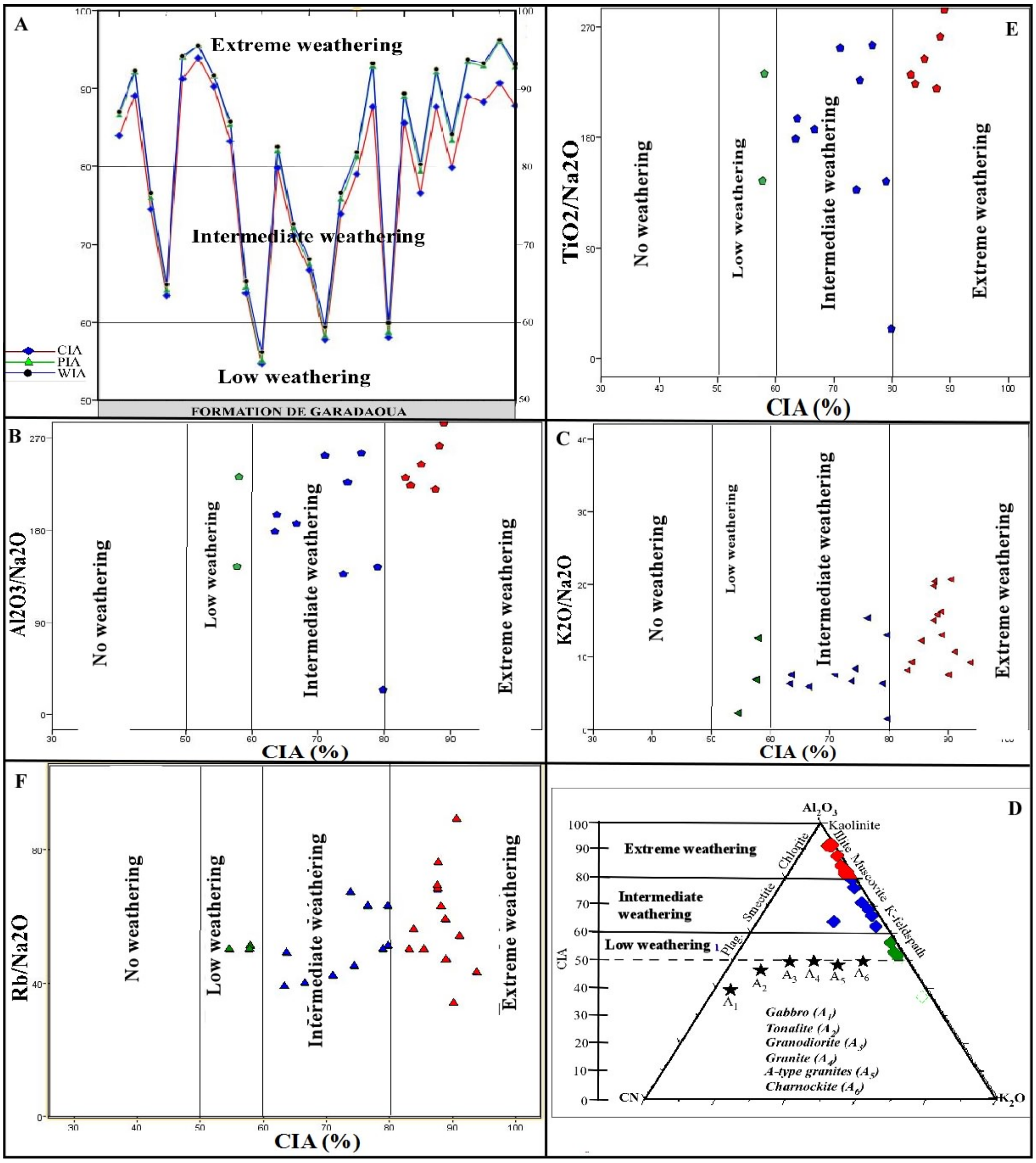


**Figure 8:** Theoretical diagrams of paleoalteration conditions. (A) Geochemical profile of (CIA), (PIA) and (CIW) Garadaoua samples [23] (B) $Al_2O_3/Na_2O$ versus CIA (C) $K_2O/Na_2O$ versus CIA (D) $Al_2O_3$, CN: CaO + $Na_2O$, K: $K_2O$ (A-CN-K): diagram of Garadaoua sediments (E) TiO2/Na2O versus CIA (F) Rb/Na2O versus CIA [8].

For [20], chemical weathering index values are reliable indicators for inferring the degree of palaeoalteration. While [8] consider the IAC as a criterion for estimating the chemical alteration of sound rocks into secondary clay products. As an indication, high values of AIC represent strong alteration of mafic rocks [20].

**Figure 8 A** presents the variations of the IAC, PIA and CIW indices in the silt-clay sediments of the Garadaoua area. The variations in these indices indicate that the Garadaoua rocks have undergone little alteration, probably due to strong erosive activity in connection with the marine transgressions that affected the Iullemmeden basin. **Figures 8B**, C and D confirm, on the other hand, the weak alteration of felsic rocks such as granitoids. These are probably the rocks of the Aïr, Hoggar and Adrar des Iforas that were affected by the T4, T5 and T6 transgressions [25].

## 6. Conclusion

The analysis of the geochemical data has made it possible to monitor the evolution of the content of major elements in order to determine: (1) the paleoclimate, (2) the alteration conditions of the source rocks at the origin of the studied formations (In Wagar and Garadaoua), (3) the nature of the analysed sediments as well as (4) their probable origin. The study shows that the samples analysed have a high silica content, which indicates the felsic origin of the sediments (granitoid alteration).

## 7. Acknowledgement

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