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Provenance of Ypresian to Miocene Sediments of the Ader Doutchi in the Akoumoutt Area, Paleoenvironment and Tectonic Context (Ader Doutchi Sub-Basin, Niger)

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Abstract

A multidisciplinary approach was used for studying the upper detrital series of the Iullemmeden Basin, which crop out in the central part of the Ader Doutchi Sub-Basin (Akoumoutt Sector). This approach includes sedimentological and geochemical analyses, involving XRF analysis of major and trace elements. The aims of this study consist to: 1) determine the provenance of the Ypresian to Miocene in age sediments of the Ader Doutchi sub-basin; 2) define their tectonic context; and 3) identify the paleoenvironment in which they were deposited. Preliminary facies analysis revealed the presence of clays, oolites, iron-rich sandstones, and in some cases, pyrite. Termitic tubing have occasionally been observed in these deposits. Geochemical analysis that specific Ader Doutchi (Ct^1) formation deposits are derived from mafic to intermediate igneous rocks of the active continental margin. It is hypothesized that some of these rocks are felsic and constitute remnants of an island arc that underwent fragmentation. The sediments supply from this are derived from the terranes of the Tuareg Shield. The studied sediments exhibit higher aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) concentration than the UCC and PASS, while silicon oxide (SiO_2) levels are lower. The values obtained for different chemical indexes (CIA, PIA, CIW, and ICV) indicate that the sediments are mature and have undergone significant fractionation and weathering. The sediments were deposited in a variety of environments, including marine, marginal littoral, and continental settings. The environmental conditions alternated between oxidizing and anoxic states. The region's climate exhibited significant variability, oscillating from hot to humid conditions to hot and arid conditions, with a marked tendency to aridification.

Keywords

Niger, Tahoua, Iullemmeden Basin, Sedimentology, Geochemistry, Paleogene

1. Introduction

The sedimentary succession within the Iullemmeden basin is distinguished by the alternation of marine and continental deposits, whose spatial and temporal boundaries are not always readily delineated with precision (Boudouresque, 1980; Boudouresque et al., 1982). During the early Cenozoic, precipitation patterns in the equatorial region of Africa favored intense weathering processes, as documented by Robinson (1973). At that time, climatic constraints generated laterites in the Iullemmeden basin, whose reworking into vast detrital outwash preserved palustrine areas. The temporal scope of these continental series extends from the Eocene epoch to the Quaternary period.

In Niger, the post-marine Tertiary detrital series was successively referred to "Niger Sandstone" by Hubert, H. (1908a, 1908b), the "Middle Niger Sandstone" by (Urvoy, 1936; Urvoy, 1942), and the "Continental terminal" (Ct^1) by Greigert (1966). The term "Continental terminal" was created by Kilian (1931) to designate continental detrital formations, which are Cenozoic in age, in the intracratonic Saharan basins and their margins. The Continental terminal series represents the terminal deposits in the Iullemmeden basin. The series includes the Ader Doutchi or Continental terminal 1 Formation (or siderolitic series), the Continental terminal 2 (Ct^2) Formation, and the Continental terminal 3 (Ct^3) Formation. According to Hanon (1984) classification system, the Ct^2 and Ct^3 formations have been grouped into the Birnin N'Konni "K" formation, which is further subdivided into K1, K2, and K3.

Earlier authors incorporated the initial ferruginous oolitic levels into the Continental terminal, delineating a basal series (Ct^1 or Ar) (Hanon, 1984; Dikouma et al., 1993). According to Dikouma et al. (1993), the presence of Ct^1 in the Eocene indicates the completion of a sedimentary cycle. According to Boudouresque, (1980) and Boudouresque et al. (1982), the Ader Doutchi Formation including ferromanganiferous and ferruginous oolitic levels, is Lutetian in age. They hypothesize the presence of an Oligocene lacuna in the Iullemmeden basin. The use of Ouledia teeth has been instrumental in establishing an Upper Ypresian age for the base of the Ader Doutchi Formation (Cappetta 1986; Miko, 1999). The Ader Doutchi Formation is believed to have been deposited during a transgressive cycle in the lower Eocene. This transgressive cycle has also been demonstrated in the coastal basin of Benin (Bio-Lokoto et al., 1998). In the Kandi basin, Issifou-Fatiou et al. (2020) attributed an Oligo-Miocene age to the Continental terminal formation. In their study, Maâzou et al. (2022) defined three members (Ar^1, Ar^2 and Ar^3) within the Ader Doutchi Formation. The Continental terminal sensu stricto displays a siderolithic facies (Ct^2 and Ct^3), which overlies the early oolitic levels. (Dikouma et al., 1993) propose the hypothesis that these specimens belong to a distinct post-Eocene sedimentary cycle.

From the perspective of sedimentology, stratigraphy, and geochemistry, further elucidation of the sedimentary deposits of the Ader Doutchi is necessary. The present study focuses on the analysis of sedimentological and geochemical features of Ypresian to Miocene age deposits that crop out in the Akoumoutt region. The aims of this study are to provide new insights regarding Ct^1 formation in the Iullemmeden basin, with a particular focus on the Ader Doutchi sub-basin. The objectives are to determine the provenance of the most recent infilling deposits in the Iullemmeden basin, with a particular focus on the Akoumoutt area and to establish the tectonic and paleoenvironmental contexts of the emplacement of these deposits.

2. Geology and Stratigraphy of the Ader Doutchi Sub-Basin

The Ader Doutchi Sub-basin, subject of this study, constitutes an integral component of the intracratonic Iullemmeden basin (Maâzou et al., 2022). The Ader Doutchi region is characterized by the prevalence of limestone and sandstones "plateaus", that are distinguished by ferruginous deposits. These plateaus exhibit altitude variations ranging from a few dozen to a hundred meters (Dikouma et al., 1993). These plateaus are often deeply incised by fossil valleys known as majias (or maggias), which themselves may be reduced to witness buttes (Dikouma et al., 1993). The Adar Doutchi, also referred to as Ader Doutchi, is situated between the 4th and 7th degrees East longitude and the 14^{th} and 16^{th} degrees North latitude (**Figure 1**). Within the geographical confines delineated by the 15^{th} parallel, a distinction is observed between the Ader Doutchi North and the Ader Doutchi South. A substantial body of research has been conducted in the Ader Doutchi region, with studies undertaken by Alzouma, (1982); Greigert (1966); Greigert et Pougnet (1965); Boudouresque, 1980; Dikouma, 1990; Hanon (1984); Laouali Idi et Konaté (2019); Laouali Idi et al. (2021a, 2021b); Maâzou et al. (2022). These studies identified six formations with a total thickness of approximately 250 meters. From bottom to top, the Alanbanya, Farin Doutchi, In-Wagar, Garadaoua, and the Continental terminal (Ct) series were distinguished.

Greigert (1966) proposed a classification system for the Niger Continental terminal deposits, distinguishing three series from bottom to top: the siderolite series of Ader Doutchi (Ct^1), the sandy lignite clays (Ct^2), and the clayey sandstones forming the top (Ct^3) (**Figure 2**). According to Millot (1964), siderolites are Characterised by the following features: 1) sandy sedimentation with cross-bedding stratifications, 2) concretionary or pisolitic ferruginous levels, 3 kaolinite lenses, and 4) silicified woods. The siderolitic or Continental terminal 1 (Ct^1 or Ar) series of the Ader Doutchi Greigert (1966), the subject of this study, is underlain by laminated black clays and marls (Daddy Gaoh, 1993). The presence of plant debris transformed into charcoal and pyrite crystals has occasionally been documented. The thickness of this series at outcrop has been measured at approximately 50 meters, with a maximum thickness of around 90 meters in the vicinity of Dogondoutchi (Guéro, 2003).

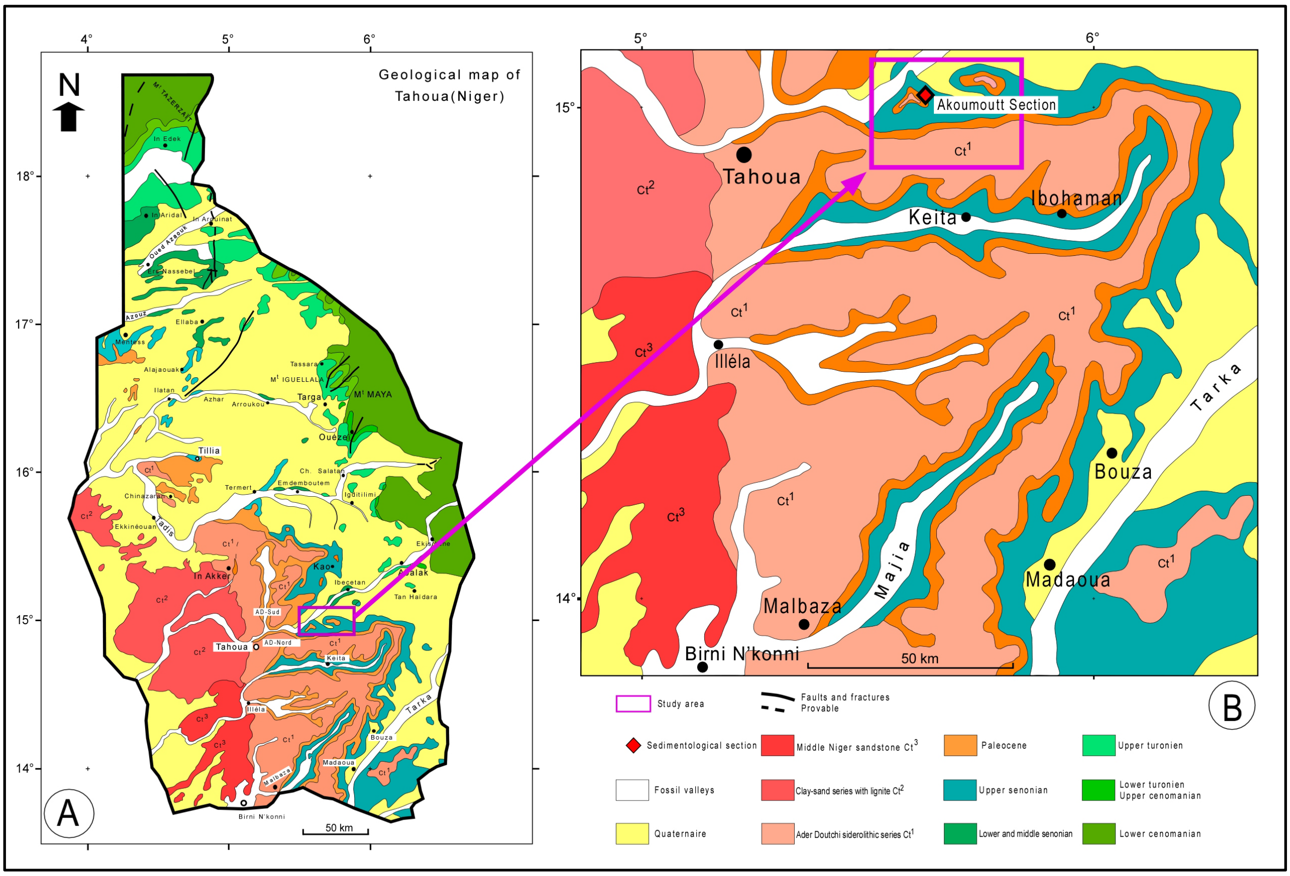

Figure 1. Geological map of Tahoua region, as delineated by Greigert et Pougnet (1965). The map shows the Ader Doutchi sub-basin, a geographical area of particular interest in this study. The following areas have been designated for this study: AD-Nord (for the northern part of Ader Doutchi sub-basin); AD-Sud (for the southern part) (Maâzou et al., 2022, 2025).

Stratigraphy of the Continental terminal
s.l. = *sensu lato* ; s.s. = *sensu stricto* (Lang et *al.*, 1986 et 1990)

Formation		Greigert (1966)	Hanon (1984)		Miko (1999)	Maâzou et *al.* (2022)
Continental terminal s.l.	Continental terminal s.s.	Middle Niger clay sandstone (Ct^3)	Formation of Birni N'Konni	K^3	Upper member	
				K^2	Lower member	
		Lignite clay-sand series (Ct^2)			Upper member	
				K^1	Lower member	
		Siderolitic series of Ader Doutchi (Ct^1)	Formation of Ader Doutchi	Ar	Upper member	Member Ar^3
						Member Ar^2
					Lower member	Member Ar^1
— — — Ravinement surface						

Figure 2. Simplified stratigraphy column of the Continental terminal series in the Iullemmeden basin.

The dissemination of these continental alteration facies into the bassins of both Africa and Europe is attributable to vertical movements affecting the basement Millot (1964). In North Africa, the Continental terminal corresponds to the Dra hamada (Gevin et al., 1975). The deposit are also found in Niger and neighboring countries, including Mali, Algeria, Tchad, Nigeria, and Benin. The presence of these sediments has also been described in a variety of West African coastal basins, including those of Senegal, Mauritania, Ivory Coast, Togo, and Benin, among others (Kogbe, 1980; Da Costa et al., 2006). Furthermore, this occurrence has been reported in Central and Southern Africa as well.

3. Materials and Methods

The sedimentological section was carried out near the Akoumoutt village (Tahoua region, Niger) at latitude N14˚57'44.2" and longitude E05˚41'31.1" (localization **Figure 1**). This section was has been completed from the final infilling deposits of the Iullemmeden basin, which span the Ypresian to Miocene age range.

Given the quality of the outcrops exposures, samples were obtained from the most representative locations. In accordance with the objectives of the present study, a detailed examination was conducted on five thin sections. These thin sections were meticulously prepared in the laboratory of the Geological and Mines Research Center of Niger (CRGM). The petrographic analysis was conducted using a LEICA DM 2700 P petrographic microscope from the Geology Laboratory of the Abdou Moumouni University (UAM, Niger).

Geochemistry analysis was conducted employing X-ray fluorescence spectrometry (XRF) on total rock samples from Continental terminal 1. The analyses were conducted at the Central Laboratory of the University of Man (U-Man) in Ivory Coast. The analysis was performed using the MESA-50 X-ray fluorescence spectrometer. The instrument set-up, calibration, and analysis were conducted using HORIBA software.

A thorough investigation encompassing geochemical and petrographic assessments of the Ypresian to Miocene deposits within the Ader Doutchi iron-clay formation yielded several diagrams. The interpretation of these diagrams has enabled us to: conduct geochemical classification, identify the tectonic context and the depositional facies; determine the source and maturity of the sediments, as well as assess paleoalteration and paleoclimates.

4. Results and Discussions

4.1. Sedimentological Facies Analysis

The sedimentological section was conducted at outcrops in the Akoumoutt area (**Figure 3**). The section is located at latitude N14˚57'41.3" and longitude E05˚41'34.4" (**Figure 1(B)**). The Ader Doutchi Formation (Ar) is characterized by deposits with an estimated thickness of approximately 30 meters, as shown in **Figure 3**. The stratigraphic organization is as follows:

- Ader Doutchi member 1 (Ar[1]) is characterized by a thickness of 4 m, comprising a succession of sedimentary rocks, including ferruginous mudstones, which are occasionally accompanied by floating ferruginous oolites, compact ferruginous clays, and compact clayey sandstones. The latter are overlied by a hardened clay surface (Figure 3, samples Ak2 to Ak6).
- Ader Doutchi member 2 (Ar[2]) has a base measuring 0.3 m consisting of two levels of ferruginous clay with termitic tubing (Figure 3, samples Ak7 and Ak8). The depositional environment of these sediments is characterized by a high degree of fracturing, resulting in the Formation of blocks measuring from decimeters to multiple decimeters in size. These blocks are particularly evident in flat areas spanning several tens of meters. The presence of blocks of ferruginous or microconglomeratic sandstone has been documented. These levels are overlain by an outcrop gap measuring approximately 13 meters in thickness, as illustrated in Figure 3. In thin sections, these deposits exhibit oolites, angular and sub-rounded quartz grains, and microfractures. These characteristics suggest that the deposits were formed nearly to the sources of sedimentation.
- Ader Doutchi member 3 (Ar[3]), which possesses a thickness of 10 meters, is composed of ferruginous sandstones, ferruginous oolites, and ferruginous mudstones (Figure 3, samples Ak9 to Ak12), which correspond to the upper part of the Ct[1] Formation (Figure 3).

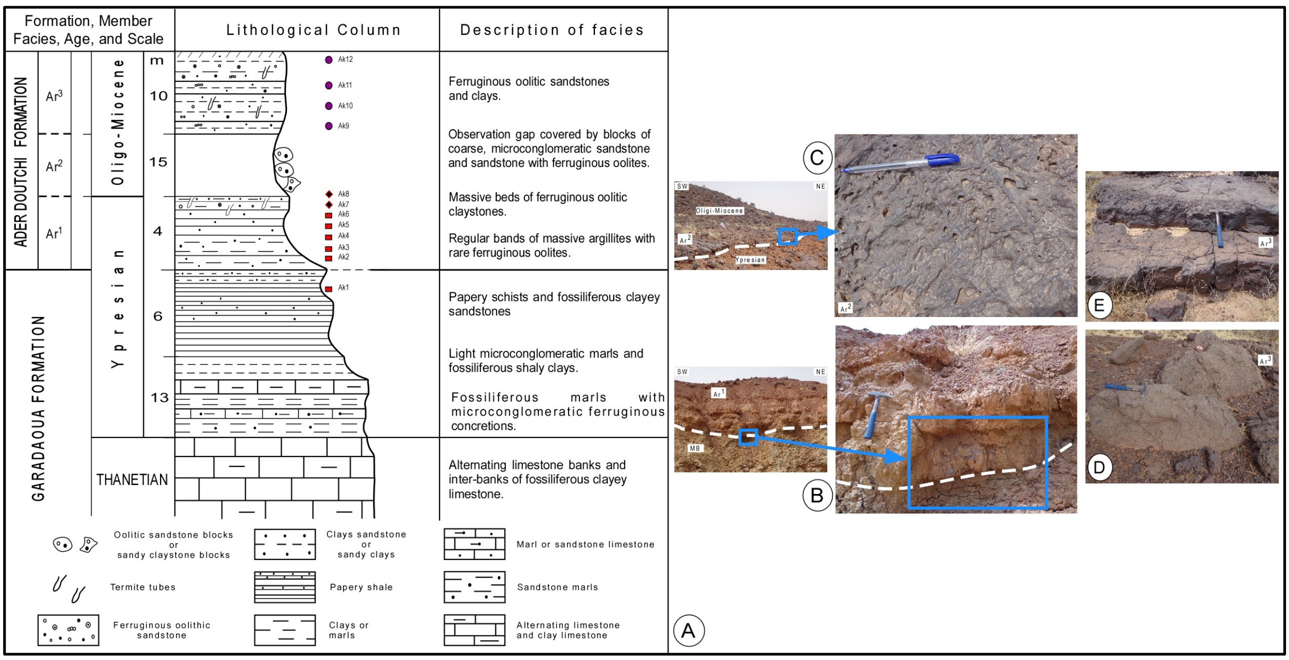

Figure 3. Ader Doutchi formation is overlain by the bedrock of the Garadaoua formation: A-lithostratigraphic section, approximately 2 kilometers southwest of the village of Akoumoutt (localization Figure 1), and various Ct[1] outcrops in the Akoumoutt area: B-Photographs illustrating the boundary between the Barmou member (MB and the Ader Doutchi 1 member (Ar[1]), C-Ferruginous mudstones exhibiting traces of burrows at the Ypresian-Oligocene Ar[2] boundary, D-Microconglomeratic blocks from the Ar[3] top, and E-Ar[3] top deposits.

4.2. Chemical Composition

4.2.1. Major Elements

According to the works of Cox et al. (1995) and Moosavirad et al. (2011), the major element composition of fine siliciclastic rocks is generally controlled by clay minerals and non-clay silicate phases. As illustrated in **Table 2**, the values of the primary oxides (Al_2O_3, SiO_2, Fe_2O_3, TiO_2, MnO, P_2O_5, K_2O, CaO, MgO, Na_2O) detected in the argillites and ferruginous sandstones within the study area are presented. Al_2O_3 was identified as the most prevalent oxide in the sample examined. The contents of the various oxides is as follow: Al_2O_3 ranges from 6.22% to 70.03% (mean of 44.35%), while SiO_2 ranges from 0% to 76.43% (mean of 27%). The ranges of Fe_2O_3, MgO, TiO_2, MnO, K_2O, and CaO are respectively, from 4.57% to 27.2% (mean of 20.6%), from 1.46% to 3.87% (mean of 2.6%), from 0.06% to 5.68% (mean of 1.32%), from 0% to 4.5% (mean of 0.6%), from 0.01% to 0.57% (mean of 0.2%), and from 0.02 to 0.44 (mean of 0.23%). The Na_2O range is from 0.46% to 3.08%. The P_2O_5 contents in four samples ranged from 0.04% to 2.44%, with an average of 1.75%. These results suggest that the samples are depleted in K_2O, CaO, Na_2O and P_2O_5.

Cox et al. (1995) reported that the K_2O/Al_2O_3 ratio values for clays are less than 0.3, and those for feldspars range from 0.3 to 0.9. This assertion is supported by the findings of (Cox et al., 1995), values ranging from 0.002 to 0.05) indicating a preponderance of clay minerals over potassium-containing minerals, such as potassium feldspars and micas. The K_2O/Al_2O_3 ratio values of the analyzed range from 0 to 0.06 (**Table 1**), indicating that the clay phase is predominant. The Ct[1] samples are distinguished by a deficiency in P_2O_5, alkalis (Na_2O and K_2O), and alkaline earths (MgO and CaO). This simultaneous depletion could be attributed to weathering conditions in the source zone (Ejeh et al., 2015). The positive correlations between the main oxides (Fe_2O_3 and P_2O_5, **Table 1**) and Al_2O_3 suggest an association with clay minerals (Das et al., 2006). The data demonstrate depletion in oxides such as SiO_2, K_2O, TiO_2, CaO and Na_2O, and an enrichment in Al_2O_3, Fe_2O_3, MgO and MnO, when compared to the average UCC and PAAS values. Most of the samples examined exhibited a substantial decrease in P_2O_5 and MnO levels relative to the mean values of UCC and PAAS (**Table 1**). The depletion of K_2O, CaO, and Na_2O in the sedimentary deposits is not only indicative of quartz dissolution, but also suggests that the sediments have undergone chemical alteration in the source area (Jin et al., 2006; Akarish & El-Gohary, 2011). Compared with UCC, the levels of major elements are considerably lower. The observed depletion of Na_2O and K_2O in the samples is indicative of a low content of Na-rich plagioclase and potassium feldspar, a result that is consistent with petrographic analysis.

On average, the shale samples have lower SiO_2 contents than the UCC, suggesting that the observed variations are likely attributed to the effect of quartz dissolution (Bauluz et al., 2000; Dokuz & Tanyolu, 2006). A comparison of the samples revealed that only one specimen (Ak5) demonstrates a higher SiO_2 content relative to the UCC and PASS (**Table 1**).

Table 1. Major elements composition of 11 samples obtained from Akoumoutt Ct, PAAS and UCC is presented.

Sample	AK2	AK3	AK4	AK5	AK6	AK7	AK8	AK9	AK10	AK11	AK12	PAAS	UCC
Al_2O_3	51.70	44.59	20.19	6.22	25.66	69.32	70.03	31.03	44.09	64.70	60.27	18.9	15.2
SiO_2	15.33	25.45	55.05	76.43	49.73	0.00	0.00	44.71	22.35	0.60	8.83	62.8	66
P_2O_5	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.29	2.44	2.18	0.2	0.2
K_2O	0.30	0.20	0.57	0.35	0.16	0.05	0.29	0.04	0.14	0.01	0.04	3.7	3.4
CaO	0.33	0.24	0.44	0.20	0.11	0.03	0.42	0.27	0.19	0.17	0.08	1.3	4.2
TiO_2	0.35	0.70	3.64	5.68	2.00	0.06	0.31	0.22	1.20	0.08	0.22	0.99	0.76
MnO	4.49	0.15	0.16	0.04	0.41	0.28	0.81	0.00	0.12	0.04	0.06	0.1	0.1
Fe_2O_3	22.11	23.35	13.14	4.57	15.62	27.06	22.48	20.47	25.35	27.20	24.99	7.18	5
MgO	3.87	3.12	3.78	2.79	3.19	2.01	2.86	1.46	2.12	1.59	1.75	2.2	2.2
Na_2O	1.59	1.25	2.79	1.88	3.08	1.45	1.48	1.11	1.79	2.35	0.46	1.2	3.9
Al_2O_3/TiO_2	148	63	6	1	13	1071	224	142	37	798	269	19	23.4
SiO_2/Al_2O_3	0.30	0.57	2.73	12.28	1.94	0.00	0.00	1.44	0.51	0.01	0.15	3.3	4.3
K_2O/Na_2O	0.19	0.16	0.20	0.19	0.05	0.03	0.20	0.04	0.08	0.01	0.09	3.1	0.9
K_2O/Al_2O_3	0.01	0.00	0.03	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.2	0.2
CIA	95.89	96.33	84.16	71.96	88.45	97.85	96.98	95.62	95.42	96.23	99.05		
PIA	96.41	96.73	85.85	73.90	88.89	97.91	97.36	95.73	95.70	96.25	99.11		
CIW	96.43	96.75	86.20	75.01	88.95	97.91	97.37	95.74	95.71	96.26	99.11		
ICV	0.55	0.65	1.21	2.49	0.94	0.44	0.40	0.76	0.70	0.49	0.46		

UCC: Upper Continental Crust, PAAS "Middle Post-Australian Shale", as defined by (Taylor & McLennan, 1985; McLennan, 2001). CIA: the chemical index of alteration is an alteration used to quantify the intensity of chemical erosion processes in a specific environment. The following indices are employed: plagioclase index of alteration (PIA), chemical index of weathering (CWI), and index of compositional variability (CVI).

4.2.2. Trace Elements

The ratios of trace elements, such as V/Ni (Breit & Wanty, 1991; Galarraga et al., 2008; Lerman, 1989; Peters & Moldowan, 1993; Lewan, 1984; Roy & Roser, 2013; Wanty & Goldhaber, 1992), or Cu/Zn (Hallberg (1976), have been used to elucidate paleoclimatic redox conditions during the deposition of sedimentary rocks. According to (Lewan, 1984), the predominant factor influencing the relative proportions of Vanadium (V) and Nickel (Ni) in sedimentary rocks is the depositional environment. Pi et al. (2014) and Zhou & Jiang (2009), posited that vanadium (V) demonstrates enhanced binding efficacy in sediments containing organic matter within anoxic environments when compared with nickel (Ni) and chromium (Cr). As proposed by Zhou et Jiang (2009), and Pi et al. (2014), variations in the V/(V + Ni) and V/(V + Cr) ratios can be used to indicate the oxygenation of the depositional environment. The ratios V/(V + Ni) and V/(V + Cr) have been identified as potential indicators of the degree of oxygenation within the depositional environment. High V/(V + Ni) ratios, ranging from 0.76 and 0.90, are indicative of sedimentary rocks formed within a deep anoxic water column

(Hatch & Leventhal, 1992; Liu et al., 2007). In Ct[1] formation, the ratio of vanadium to nickel (V/(V + Ni)) ranges from 0.6 à 0.93 (**Table 2**). A single sample was found to have a zero V/(V + Ni) (**Table 2**). The data indicates that the ferruginous sandstones and clays of the Akoumoutt section were formed in a marine, margino-littoral, and continental environment, predominantly in anoxic shallow water (**Table 2** and **Figure 14**). The presence and nature of the ferruginous oolites (Oγ, Oα) indicate a shallow water environment. The present study investigates the depth of the Ader Doutchi Formation during its emplacement in the study area.

Table 2. A comprehensive examination of the trace elements present in samples from the Ct[1] Formation in the Akoumoutt section. Elemental concentrations are expressed in parts per million (ppm). The depositional environments were estimated from the Sr/Ba ratio.

Formation	**Ader Doutchi Formation or Ct[1]**												
Member	**Ar[1]**				**Ar[2]**				**Ar[3]**				
Sample	AK2	AK3	AK4	AK5	AK6	AK7	AK8	AK9	AK10	AK11	AK12	UCC	PAAS
Ni	48	66	181	111	113	82	133	30	57	39	44	44	55
Zn	168	301	509	200	306	310	496	68	195	117	212	71	85
Zr	79	117	4091	7391	1605	40	275	110	378	6	30	190	210
Nb	164	210	960	2486	321	293	1368	462	206	152	228	12	19
V	243	485	751	1557	302	209	199	0	527	421	580	150	107
Cr	224	416	0	0	62	386	387	88	760	378	370	83	110
Cu	10	32	68	57	14	4	59	61	61	13	25	25	50
Sr	164	171	394	240	98	30	113	180	41	14	29	350	200
Rb	61	83	120	73	70	101	48	46	85	111	94	-	-
Ba	98	43	432	379	273	34	395	104	37	25	35	550	650
V/(V + Ni)	0.84	0.88	0.81	0.93	0.73	0.72	0.60	0.00	0.90	0.92	0.93		
V/(V + Cr)	0.83	0.85	1.00	1.00	0.98	0.71	0.63	0.00	0.75	0.85	0.88		
V/Ni	5.06	7.35	4.15	14.03	2.67	2.55	1.50	0.00	9.25	10.79	13.18		
Sr/Cu	16.4	5.34	5.8	4.21	7	7.5	1.92	2.95	0.67	1.07	1.16		
Cr/Ni	4.7	6.3	0.0	0.0	0.5	4.7	2.9	2.9	13.3	9.7	8.4		
Sr/Ba	1.67	3.98	0.91	0.63	0.36	0.88	0.29	1.73	1.11	0.56	0.83		
Environment	Marine		Margino-littoral to continental						Continental				

V/Ni ratios exceeding 3 are indicative of a reducing environment, while ratios ranging between 1.9 and 3 signify a suboxic environment (Galarraga et al., 2008). The Ct[1] samples obtained from the Akoumoutt area exhibit a V/Ni ratio ranging from 0 to 14, with an average value of 6.41, as shown in **Table 2**. This finding suggests that the sediments were deposited in environments characterized by predominantly reducing conditions (Ar[1] member), suboxic to reducing anoxic conditions (Ar[2] member), and reducing conditions (Ar[3] member). These results are consistent with the presence of pyrite dispersed in the rock matrix, as pyrite is indicative of a reducing environment and shallow water (Gier et al., 2008; Schieber & Baird, 2001). The observations are consistent with the findings from thin section analysis, which indicated the presence of pyrite and oolites in the samples studied (**Figure 4**). The "Ader Doutchi siderolite series" was given this designation due to the significant alteration of pyrite to siderolite, as described by (Alzouma, 1982, 1994; Dikouma et al., 1993; Greigert, 1966; Miko, 1999). The Ader Doutchi siderolite series is underlain by laminated black clays and marls (Daddy Gaoh, 1993). As indicated in the research by Daddy Gaoh (1993), there have been documented cases of plant debris being transformed into charcoal and pyrite crystals. However, traces of burrows and significant bioturbation have been detected in some Ct^1 deposits, particularly in the Ar^2 member of the study area (**Figure 3(C)**). According to (Ben-Awuah et al., 2017), this phenomenon suggests periodic aeration of the sediments, thereby facilitating the activities and survival of burrowing organisms and bioturbators. In summary, an alternating pattern between oxic and anoxic conditions was observed during the establishment of Ct^1 in the Akoumoutt sector. This finding is consistent with the alternation of wet and dry periods in the Ader Doutchi, which transitions from the Ypresian to Miocene epoch.

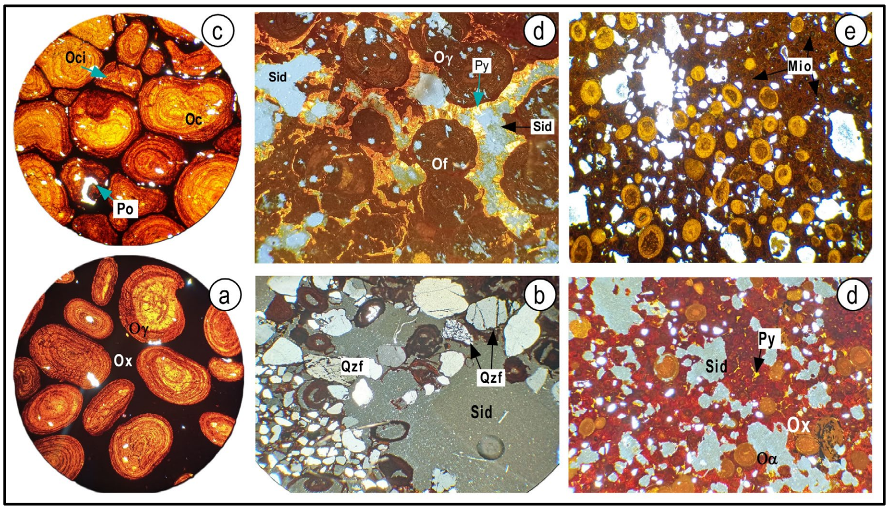

Figure 4. Microphotograph of thin sections from the Oligo-Miocene deposits of Continental terminal 1. Meaning of abbreviations used: "Ox" denotes iron oxide, "Po" indicates port, "Qzf" represents fractured quartz, "Sid" signifies siderite, "Py" is pyrite, "Of" is fractured oolite, "Oc" is composite oolite, "Moi" is micro-oolite, "Oγ" is gamma oolite, and "Oα" is alpha oolite.

According to Cullers (2000), Cullers et Podkovyrov (2000), and Cullers et al. (1988), the Cr/Th ratio is indicative of a mafic source when it ranges between 25 and 500. According to McLennan (2001), and Taylor et McLennan (1985), the Cr/Th ratio value in the UCC is 7.76. The mean ratio of Ct^1 samples from the Akoumoutt area ranges from 0 to 190, with a mean of 38.5, which is indicative of a mafic source (**Table 2**). Two samples exhibited a Cr/Th ratio of 0, while one sample demonstrated a ratio of 5 (**Table 2**). This finding further corroborates the hypothesis that felsic or intermediate sources are also present.

Cr/V values for Ct[1] ferruginous clays range from 0 to 1.94, with an average of 0.88, and are relatively close to those for UCC (0.8) and PAAS (0.7) (**Table 2**). Elevated values relative to those of UCC and PASS are indicative of Cr enrichment relative to V, while comparatively lower values are indicative of Cr depletion relative to V. Ultramafic rocks are characterized by their tendency to exhibit high Cr/V ratios (McLennan, 1993). Consequently, the low Cr/V ratios recorded in the samples confirm the significant absence of sediments originating from ultramafic rocks in the deposits studied. The lower Cr/V values indicate a low input of sediments from mafic rocks.

Table 3. Correlation between the major and trace elements present in samples extracted from the Ct[1] formation within the Akoumoutt area.

	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	MgO	Na_2O	Ni	Cu	Zn	Zr	Nb	V	Cr	Sr	Rb	Ba
Al_2O_3	1																			
SiO_2	−0.99	1																		
P_2O_5	0.41	−0.45	1																	
K_2O	−0.52	0.51	−0.52	1																
CaO	−0.19	0.18	−0.39	0.74	1															
TiO_2	−0.85	0.86	−0.32	0.67	0.18	1														
MnO	0.18	−0.20	−0.24	0.24	0.31	−0.21	1													
Fe_2O_3	0.89	−0.92	0.48	−0.67	−0.28	−0.94	0.09	1												
MgO	−0.35	0.33	−0.59	0.83	0.56	0.41	0.55	−0.46	1											
Na_2O	−0.44	0.41	−0.18	0.43	0.17	0.46	−0.04	−0.42	0.44	1										
Ni	−0.38	0.41	−0.49	0.81	0.48	0.61	−0.15	−0.59	0.62	0.57	1									
Cu	−0.48	0.49	−0.23	0.49	0.61	0.46	−0.35	−0.45	0.05	0.01	0.40	1								
Zn	0.03	0.00	−0.41	0.64	0.46	0.22	−0.09	−0.19	0.56	0.30	0.88	0.26	1							
Zr	−0.80	0.82	−0.31	0.64	0.18	0.98	−0.20	−0.94	0.35	0.40	0.59	0.44	0.19	1						
Nb	−0.51	0.57	−0.37	0.56	0.31	0.78	−0.18	−0.80	0.22	0.12	0.56	0.55	0.28	0.85	1					
V	−0.60	0.61	0.03	0.47	−0.01	0.87	−0.25	−0.72	0.20	0.17	0.35	0.32	0.05	0.88	0.72	1				
Cr	0.66	−0.70	0.48	−0.46	−0.26	−0.56	−0.06	0.76	−0.37	−0.37	−0.43	−0.11	−0.11	−0.61	−0.47	−0.28	1			
Sr	−0.71	0.71	−0.59	0.86	0.70	0.66	0.07	−0.73	0.64	0.33	0.63	0.57	0.40	0.65	0.50	0.40	−0.68	1		
Rb	0.07	−0.10	0.45	0.07	−0.23	0.14	−0.34	0.13	−0.05	0.29	0.19	−0.20	0.19	0.12	−0.21	0.29	0.11	0.03	1	
Ba	−0.52	0.57	−0.51	0.80	0.59	0.70	−0.06	−0.78	0.55	0.49	0.89	0.54	0.66	0.71	0.77	0.42	−0.62	0.69	−0.15	1

According to Garver et al. (1996), a Cr/Ni ratio greater than 3 indicates Cr enrichment of fine-grained sediments, which is linked to the process of sediment fractionation. Consequently, Cr/Ni values less than 3 are indicative of Cr depletion in rocks. In samples from the Akoumoutt area, Cr/Ni values range from 0 to 13.33, with an average of 4.86. This observation suggests the presence of Cr enrichment in the rock Formation. This finding indicates a Cr enrichment of Ct[1] sediments (**Table 2**). The analysis yielded a statistically negative correlation between Cr and Ni (**Table 3**). According to Garver et al. (1996), Cr/Ni values greater than 3 suggest substantial sediment fractionation of Ct[1] deposits within the Akoumoutt area (**Table 2**).

As demonstrated in **Table 3**, a correlation matrix illustrates the relationship between major oxides (Al_2O_3, SiO_2, Fe_2O_3, TiO_2, MnO, P_2O_5, K_2O, CaO, MgO, Na_2O) and specific elements (Ni, Cu, Zn, Zr, Nb, V, Cr, Sr, Rb, and Ba). In addition, a robust negative correlation was observed between SiO_2 concentration and Al_2O_3 as well as Fe_2O_3, as evidenced in **Table 3**. This result suggests that the majority of SiO_2 is present in detrital form.

4.3. Geochemical Index and Classification

As part of the present study, an evaluation of sediment composition, maturity, and weathering was conducted. In addition to the calculation of geochemical indices, such as CIA, PIA, ICV, and CIW, several parameters must be taken into consideration. The analyses were based on the formulas and diagrams proposed by Cox et al. (1995); Cullers (2000); Hofmann et al. (2001); Nesbitt & Young (1982); Roser & Korsch (1988).

The intensity and duration of weathering in clastic sediments can be assessed by examining the relationships between alkaline elements and alkaline earths elements (Nesbitt & Young, 1996). The impact of chemical weathering on the composition of siliciclastic sedimentary rocks can be evaluated by measuring the degree of chemical weathering. Many weathering indices have been documented in the extant literature; however, the most frequently employed are the chemical index of alteration (CIA), as proposed by earths (Nesbitt & Young, 1982), and the chemical index of weathering (CIW), as developed by (Harnois, 1988). It is imperative to acknowledge that the latter is calculated differently from the CIA. The central chemical index of alteration (CIA) has been assigned the mission of monitoring the progressive conservation of feldspars into clay minerals. The application of this index is presented on the fact that feldspars are the most abundant minerals in the upper continental crust and that the major process involved in the chemical weathering is the alteration of feldspars to form clay minerals (McLennan, 2001; Nesbitt & Young, 1982). The CIA has been used for monitoring the progressive alteration of feldspars into clay minerals. The application of this index is predicated on the fact that feldspars are the most abundant minerals in the upper continental crust and that the major process involved in chemical weathering is the alteration of feldspars to form clay minerals McLennan (2001); Nesbitt et Young (1982). Nesbitt et Young (1982) developed the chemical index of alteration (CIA) formula, which is employed to assess the degree of chemical alteration. The chemical index of alteration (CIA) formula to assess the degree of chemical alteration is: $CIA = [Al_2O_3/(Al_2O_3 + CaO^* + K_2O + Na_2O)] \times 100$.

Despite the absence of petrographic analysis, the low concentration of calcium oxide (CaO) indicates that the calcium oxide present in the samples is associated with silicate phases. This assertion is supported by Fedo et al. (1995). As indicated by Nesbitt & Young (1982), a CIA of 100 is indicative of complete transformation of feldspar to clay minerals, such as kaolinite.

According to Jacobson et al. (2003) and Liu et al. (2007), an increased intensity of chemical weathering may indicate a decrease in tectonic activity and/or a climate shift towards warmer, wetter climatic conditions, which are more conducive to chemical weathering in the source region. In environments characterized by arid or cold conditions, sediment is primarily attributable to abrasion and attrition processes. These processes entail the physical disintegration of the parent materials, accompanied by negligible chemical alteration. Additionally, the degree of chemical weathering was assessed using an additional chemical index of weathering (CIW).

Another effective measure for calculating the degree of chemical weathering is the plagioclase index of alteration (PIA, Fedo et al., 1995), calculated by the following formula: the proportion of insoluble inorganic compounds (PIA) is calculated using the following formula: the proportion of insoluble inorganic compounds (PIA) is calculated using the following formula: $PIA = [(Al_2O_3 - K_2O)/(Al_2O_3 + CaO + Na_2O - K_2O)] \times 100$.

However, it should be noted that the CIA and PIA may not provide satisfactory results, particularly in samples with significant variations in calcium content (Cullers, 2000). To achieve more reliable results, particularly in cases where high concentrations of CaO are present, Cullers (2000) developed a formula to calculate the degree of chemical weathering in sandstones with high CaO content. This formula, referred to as the chemical index of weathering (CIW), is expressed as $CIW = [Al_2O_3/(Al_2O_3 + Na_2O)] \times 100$. The values of the CIW (ranging from 75 to 99) obtained from the samples indicate intense to moderate weathering of first-cycle sediments. Alternatively, these values may also reflect recycling under semi-arid to semi-humid climatic conditions. CIW values also signify a dominant felsic source and sediment recycling processes (Ejeh et al., 2015). As Harnois (1988) observed, the variability of K+ during weathering can introduce error into the CIA, as Nesbitt and Young (1982) presumed that K_2O was a mobile component. According to Harnois (1988), the presence of K^+ can facilitate the formation of K minerals or be adsorbed onto other clay minerals through ion exchange, even after entering solution.

The CIW values for the analyzed samples were (**Table 1**) range from 75 to 99, with an average of 85. CIW values are similar to those of CIA and PIA. The elevated CIW values (nearly reaching 100), detected in the examined specimens are suggestive of substantial chemical weathering. We can see that the CIW index increase in proportion to the degree of Na and Ca depletion in the sediments. This result is consistent with the documented negative correlation between Al_2O_3, Na_2O, and CaO (**Table 3**). According to Harnois (1988), the discrepancy between CIW values for parent rock and sediments serves as an indicator of the extent of chemical alteration experienced by the weathered material.

The CIA, PIA, and CIW values in Ct[1] of the study area demonstrate respective variations ranging from 72 to 99, 74 to 99, and 75 to 99, as illustrated in **Figure 5** and in **Table 1**. Nesbitt et Young (1982) reported CIW values of 0 for diopside, 30 to 40 for fresh basalt, 45 to 55 for granites and granodiorites, 50 for albite, anorthite, and unweathered potassium feldspars, and 75 for muscovite. Additionally, the values reported for illite, montmorillonite, and beidellite range from 75 to 85, while kaolinite and chlorite exhibit values approaching 100. The CIA values found in most samples from Ct[1] in the Akoumoutt sector are above 85, consistent with the presence of kaolinite, bauxite, and laterite, identified as the main minerals. The CIA, PIA, and CIW values indicate substantial alterations in the deposits under study (**Figure 5**). A single specimen displays indications of moderate weathering, as illustrated in **Figure 5**. The CIA values of the Ct[1] ferruginous clay samples from the Akoumoutt section (ranging from 72 to 99) (**Table 1**) clearly indicate intense chemical alteration.

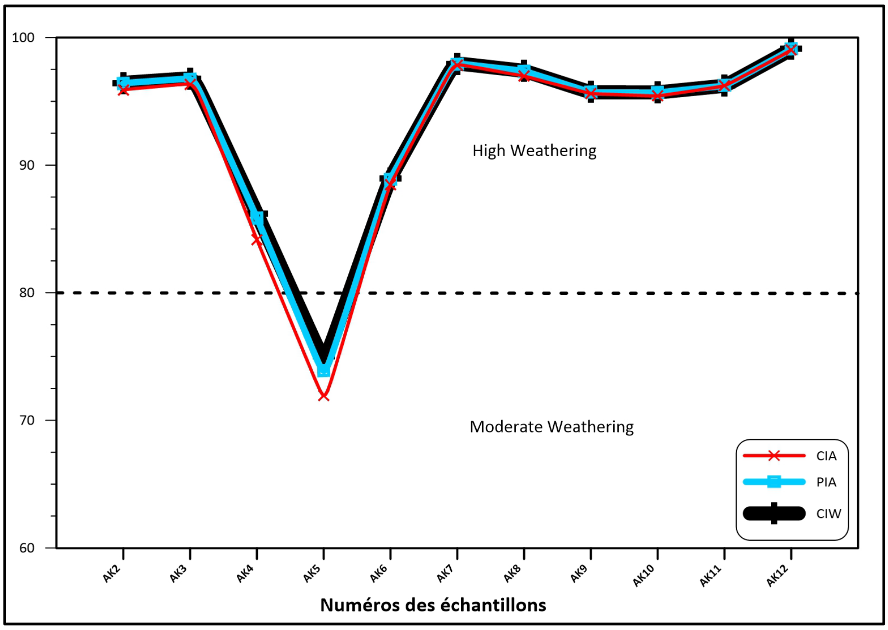

Figure 5. Geochemical profiles of Ypresian to Miocene Ct[1] deposits, as proposed by Dill (1986), delineated by the CIA, PIA and CIW.

The compositional variations observed in the samples were mapped onto the Log($Fe_2O_3^t/K_2O$) versus Log(SiO_2/Al_2O_3) binary diagram proposed by Herron (1988). The observed variations suggest that the Ct[1] series in the Akoumoutt area is predominantly composed of ferruginous clays (**Figure 6**).

4.4. Sediment Provenance and Maturity

The Roser et Korsch (1988) diagram was used to determine the provenance of Ypresian to Miocene sediments in the Ader Doutchi sub-basin (**Figure 7**). The F1 and F2 discrimination factors proposed by Roser et Korsch (1988) were employed to estimate sediment provenance. The projection of samples from the Ypresian to

Miocene in age formation in the Akoumoutt area, reveals the prevalence of a mafic igneous source (Figure 7). The presence of detrital quartz grains has been used as a key indicator of the emplacement of the Continental terminal 1 deposits (Figure 7). The detrital quartz source is attributed to the sediments recycling, in conjunction with a gradual input of feldspar (Abdou Dodo, 2021).

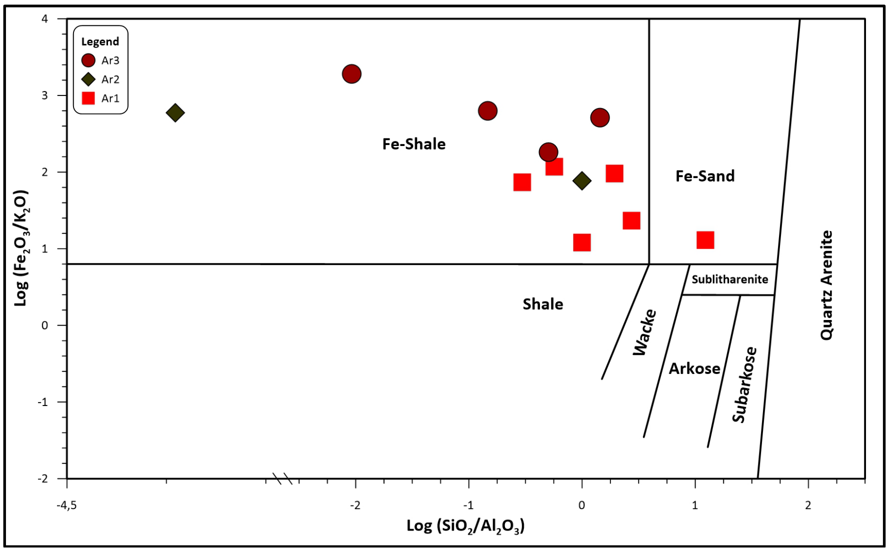

Figure 6. Chemical classification of Ct^1 sediments from the Akoumoutt area in the Log ($Fe_2O_3^t/K_2O$) versus Log(SiO_2/Al_2O_3) binary proposed by Herron (1988).

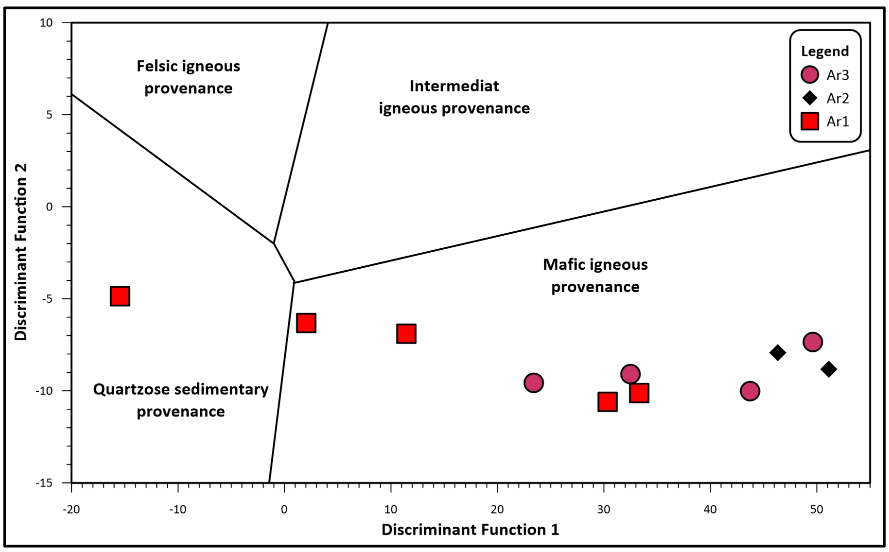

Figure 7. Provenance of Ypresian to Miocene sediments in the Ader Doutchi sub-basin, as determined by the F1 versus F2 discrimination diagram proposed by Roser et Korsch (1988).

The ratios of TiO_2 versus Zr (Figure 8) and TiO_2 versus Al_2O_3 (Figure 9, Figure 10) demonstrate that most sediments originate from felsic igneous rocks, with the presence of sediments from intermediate sources. The determination of sediment sources from TiO_2 and Zr ratios is based on the premise that these are the most stable heavy minerals and can retain the geochemical signatures of source rocks (Morton, 1985). As illustrated in **Figures 8-10**, a discernible correlation is apparent between mafic and intermediate igneous sources. The majority of Ct[1] samples are classified as originating from granodioritic and alkaligranitic sources (**Figure 10**). These results are consistent with those of studies conducted by Issifou-Fatiou et al. (2019), Issifou-Fatiou et al. (2019) and Issifou-Fatiou et al. (2020), in the undifferentiated Continental terminal deposits of the Kandi basin (Benin).

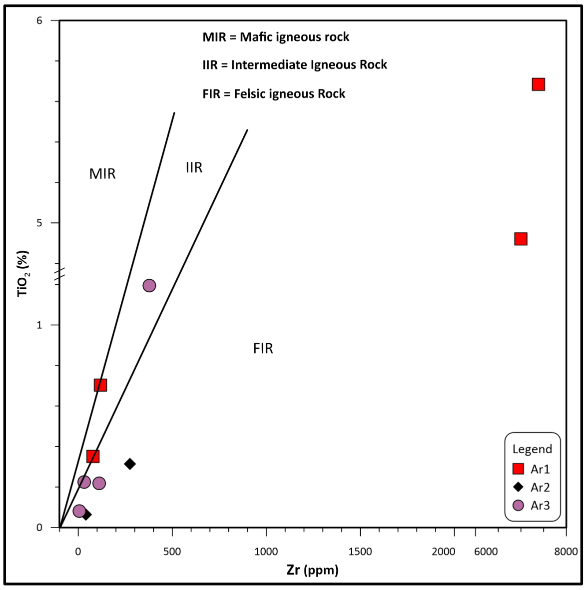

Figure 8. Scatter plot of TiO_2 versus Zr for Ct[1] samples from the Akoumoutt area, following the modifications of Ben-Awuah et al. (2017) to the original study Hayashi et al. (1997).

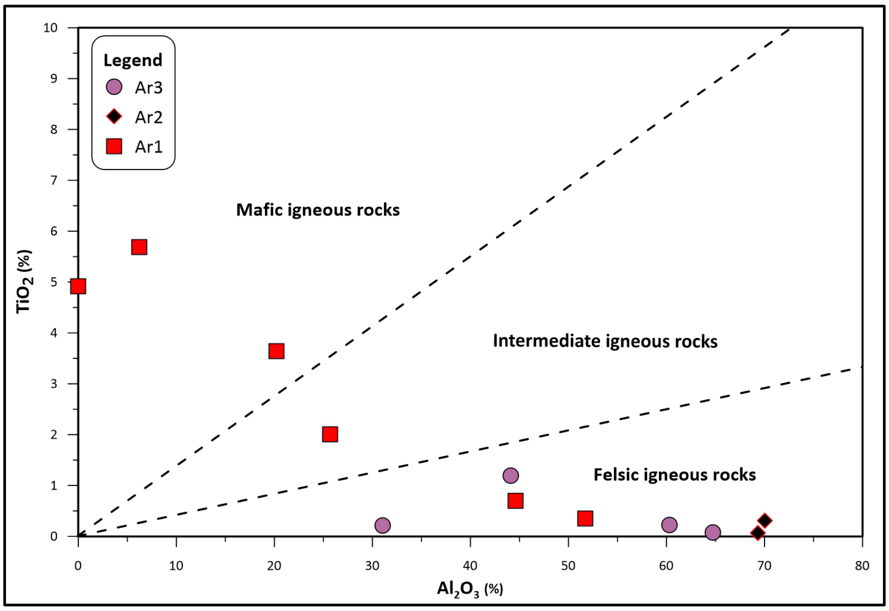

Figure 9. The provenances of sediments from the Ypresian to Miocene in age of the Ader Doutchi sub-basin delineated based on the TiO_2 versus Al_2O_3 binary diagram proposed by Hayashi et al. (1997).

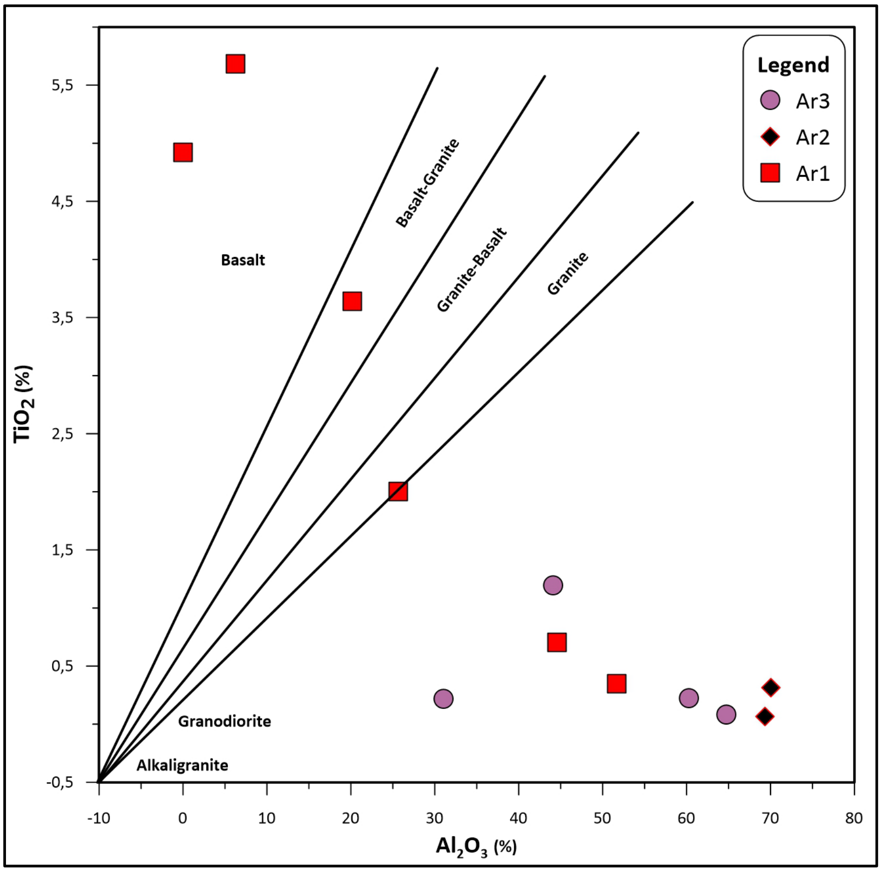

Figure 10. Al_2O_3 versus TiO_2 binary diagram of samples from the Ader Doutchi Formation which is Ypresian to Miocene in age, based on the diagram proposed by Floyd et al. (1989).

Floyd et al. (1989) employed Al_2O_3/TiO_2 curves to determine the provenance of siliciclastic sediments. The Ct[1] ferruginous clay samples from the Akoumoutt area fall within the granodiorite and alkaligranite range of the Al_2O_3/TiO_2 diagram (**Figure 10**), indicating that the sediments originate from acid igneous rocks. According to He et al. (2010) and Dai et al. (2020), the Al_2O_3/TiO_2 ratio and SiO_2 content exhibit variation in igneous rocks. According to Hayashi et al. (1997), the Al_2O_3/TiO_2 ratio varies between 3 and 8 for mafic igneous rocks, between 8 and 21 for intermediate rocks, and between 21 and 70 for felsic rocks (Ben-Awuah et al., 2017). Two samples have Al_2O_3/TiO_2 ratios of 1071 (Ak7) and 798 (Ak11). The Al_2O_3/TiO_2 ratio of the majority of Ct[1] samples from the Akoumoutt area ranges from 1 to 269, with an average of 100, which suggests that the source rocks are likely intermediate or reworked igneous rock sediments. The range of SiO_2 values in the samples is from 0% to 76%, with an average of 27%.

The mean SiO_2 (μ 44%) of the base levels (Ar[1]) approximates that of mafic sources, while the Ar[2], which represents a sedimentation gap, exhibits virtually no silica ($SiO_2 < 0\%$). Similarly manner, Ar[3] exhibits an average SiO_2 content of 19%. The low SiO_2 values observed in the analyzed samples can be attributed to its dissolution in favor of Al_2O_3, as demonstrated in **Table 1**. This dissolution could also be explained by the low SiO_2 content in relation to UCC (**Table 1**) (Bauluz et al., 2000; Dokuz & Tanyolu, 2006).

The results of projecting geochemical data in the diagrams of Hayashi et al. (1997), modified by Ben-Awuah et al. (2017) and Floyd et al. (1989), indicate a dominance of felsic sources. Conversely, the projection of samples from the Ct[1] Formation in the Roser et Korsch (1988) diagram reveals a preponderance of mafic sources. A comprehensive analysis of the Ct[1] samples in the V-Ni-Th*10 ternary diagram, as delineated by Bracciali et al. (2007), reveals that the sediments under scrutiny are derived from both mafic and felsic sources (**Figure 11**).

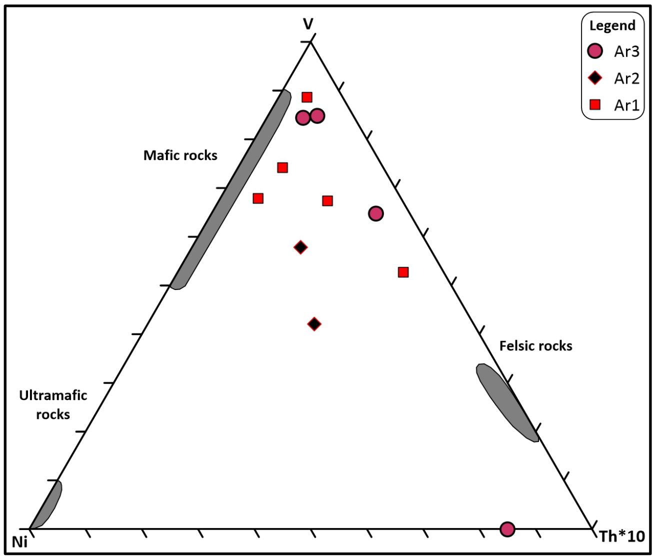

Figure 11. The V-Ni-Th*10 ternary diagram (Bracciali et al., 2007), provides a visual representation of the complex interplay among the elements. The shaded regions in the **Figure** delineate the composition of ultramafic, mafic, and felsic rocks. The ferruginous sandstones and mudstones of the Akoumoutt Ct[1] are near the mafic and intermediate source rocks. However, a single sample has been identified as originating from a felsic source.

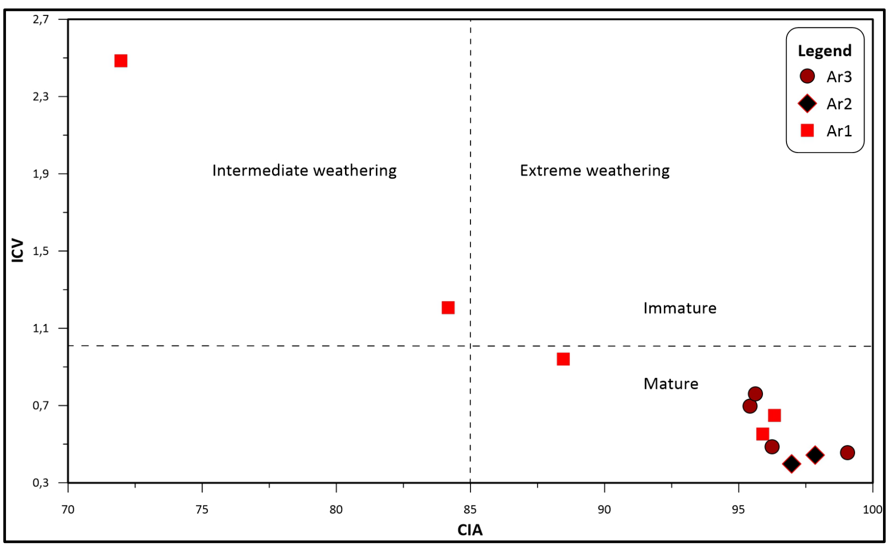

Figure 12. Transition from Ypresian to Miocene sediments within the Ader Doutchi subbasin determination based on the ICV versus CIA diagrams presented by Larbi (2003).

The results of sample projection, as illustrated in the ICV versus CIA binary diagram proposed by Larbi (2003), demonstrate that the sediments of the Ct[1] Formation are predominantly mature and have undergone significant alteration (**Figure 12**). The sedimentary deposits from the Ader Doutchi Formation demonstrate notable signs of weathering, with occasional instances of moderate weathering (**Figure 12**). A comprehensive analysis of the chemical and petrological properties of the Ct[1] deposits reveals significant alterations (**Figure 4** and **Figure 5**). These alterations are accompanied by a notable absence of Na_2O and K_2O, along with relatively high SiO_2 (mean of 44%) at the base (Ar[1]) (**Table 1**). These observations are essential in determining the maturity of the Ader Doutchi Formation deposits, suggesting the presence of an advanced sedimentary process. As demonstrated in **Table 1**, the ICV values for the marine series range from 1.13 to 4.2 (>>1), indicating consistency with compositional maturity.

4.5. Paleoenvironment and Tectonic Setting

The climate is one of the primary factors that influence the mineralogy, weathering, and chemical composition of sedimentary rocks (Boggs, 2009). The SiO_2 versus $Al_2O_3 + K_2O + Na_2O$ binary diagram in **Figure 13**, proposed by Suttner et Dutta (1986), has been employed to ascertain climatic conditions. Intense chemical weathering has been demonstrated to be strongly associated with a warm, humid climate (Nesbitt & Young, 1996). Lerman (1989) proposed the Sr/Cu ratio as a significant indicator of paleoclimatic conditions. Sr/Cu ratios that exceed 5 are indicative of a warm, arid climate, while Sr/Cu ratios ranging from 1.3 to 5 suggest a warm, humid climate (Lerman, 1989). The Sr/Cu ratios of the samples under study range from 0.67 to 16.40 (**Table 2**). The values observed in this study align with the data represented in the SiO_2 vs. $Al_2O_3 + Na_2O + K_2O$ graph in **Figure 13**. This finding suggests the presence of a climate characterized by variations in temperature and precipitation, ranging from hot and humid to hot and arid conditions, during the development of the Ct[1] Formation in the Akoumoutt area (**Figure 13**). The results of the analysis reveal a correlation between high CIA values and the observed alteration in the paleoenvironments (**Table 1**).

The Sr/Ba ratio has been identified as a reliable indicator of environmental salinity in sedimentary rocks (Sarki Yandoka et al., 2015). Deng et Qian (1993) hypothesized that low Sr/Ba ratios are indicative of low salinity associated with a freshwater environment, while high Sr/Ba ratios are indicative of high salinity associated with a marine environment. According to studies by Schmitz and Thompson et al. (1997), Sr and Ba exhibit sensitivity to paleosalinity variations and are more concentrated in seawater than in freshwater. The authors demonstrated that variations in sedimentary environments have the potential to disrupt the correlation between these factors. Barium (Ba) is readily precipitated as $BaSO_4$, while strontium (Sr) exhibits greater mobility due to its higher solubility compared to that of Ba (Van Os et al., 1991; Van Beek et al., 2003). Consequently, the Sr/Ba ratio has been employed as a proxy for paleoenvironmental changes in sedimentary rocks Van Os et al. (1991). A Sr/Ba ratio greater than 1 indicates the presence of a marine deposit, whereas a ratio less than 1 is indicative of a continental deposit Van Os et al. (1991). The Sr/Ba ratio values for the Ct^1 ferruginous mudstones and oolitic ferruginous sandstones in the study area range from 0.36 à 3.98 (**Table 2**). Four of the 11 samples (Ak2, Ak3, Ak9, and Ak10), exhibited a Sr/Ba ratio greater than 1, suggesting a sedimentation in a marine environment (**Table 2**). The seven remaining samples (Ak4, Ak5, Ak6, Ak7, Ak8, Ak11, and Ak12) that exhibit Sr/Ba ratios below 1, are indicative of a sedimentation in a continental environment (**Table 2**). The Sr/Ba ratio values of the Akoumoutt sector sediments indicate fluctuations in sea level, with the installation of a marine to intermediate domain during the deposition of the Ar^1 and Ar^2 members and the return to open marine conditions during the sedimentation of the Ar^3 member (**Figure 14**). This phenomenon is indicative of the confluence of both fresh and marine water sources, exhibiting intermediate salinity characteristics. According to Ben-Awuah et al. (2017), this phenomenon is characteristic of deltaic environments, such as the Western Baram Delta, where freshwater flows into the ocean. The deltaic and marine depositional paleoenvironments determined in this study are consistent with the findings of research in the Continental terminal of the Iullemmeden Basin by Miko (1999) and Lang et al. (1990). The authors demonstrated that the Ader Doutchi rubefied series represents a transitional unit deposited in marine to margino-littoral and continental environments.

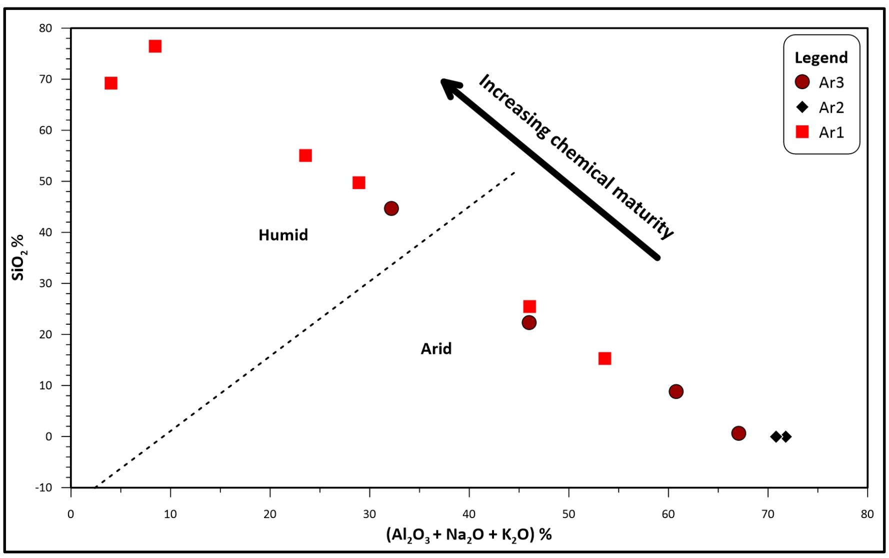

Figure 13. Paleoclimatic discrimination of the Continental terminal deposits in the Akoumoutt area, is derived from the SiO_2 versus ($Al_2O_3 + K_2O + Na_2O$) binary diagram of Suttner & Dutta (1986).

The geochemical signatures of sediments have been used to determine their provenance (Armstrong-Altrin, 2015; Nesbitt & Young, 1982; Roser & Korsch, 1986, 1988). The SiO_2/Al_2O_3 ratio, as previously theorized by these authors, demonstrates sensitivity to both the recycling process and weathering. The SiO_2/Al_2O_3

ratio has historically served as a proxy for evaluating the maturity of sediments. In unweathered igneous rocks, the typical SiO_2/Al_2O_3 ratio ranges from 3 in basic environments to 5 in acidic environments, while it is 5-6 in sedimentary rocks (Armstrong-Altrin, 2015). Nesbitt et Young (1982) proposed the discriminant diagram using K2O/Na2O versus SiO_2 to establish various tectonic settings of clastic rocks (**Figure 15**). Maynard et al. (1982) proposed the SiO_2/Al_2O_3 versus K_2O/Na_2O diagram to further clarify tectonic discrimination (**Figure 16**). Projection of the samples from Ct[1] in the Akoumoutt area in the diagrams of Nesbitt et Young (1982) and Maynard et al. (1982) indicates that the sediments originate essentially from an oceanic island arc, in particular an evolved arc with felsic plutonic detritus (**Figure 15** and **Figure 16**). Two samples suggest emplacement in a context of an active continental margin (**Figure 15** and **Figure 16**). These sediment sources could be the proximal mountainous reliefs that constitute the Touareg shield, such as the Aïr, Adrar des Iforas, and Hoggar mountains. During the Cenozoic, the Tuareg Shield (Aïr, Adrar des Iforas and Hoggar), which corresponds to an ancient Pan-African active margin associated with island arcs, underwent bulging (Liégeois, 2019) and represents a province with high topography. Consequently, the crystalline and crystallophyllous rocs on the various terranes of the Tuareg Shield could represent the main sources of detrital sediments filling the Ypresian to Miocene Ader Doutchi sub-basin.

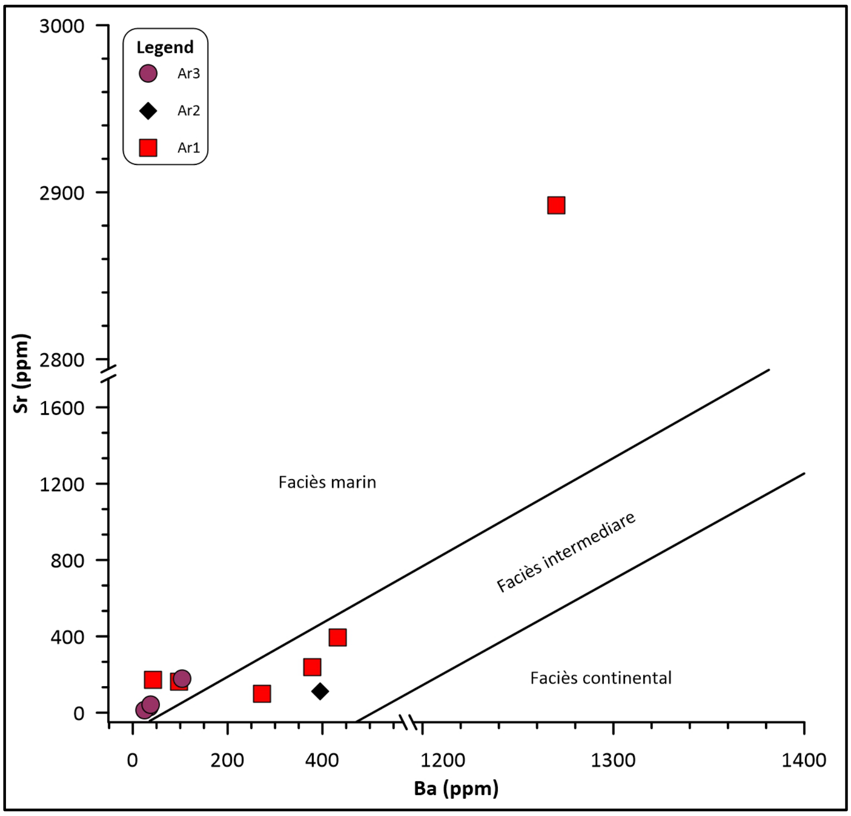

Figure 14. The projection of the Ader Doutchi Formation samples is represented in the Sr versus Ba diagram, as proposed by Zuo et al. (2020).

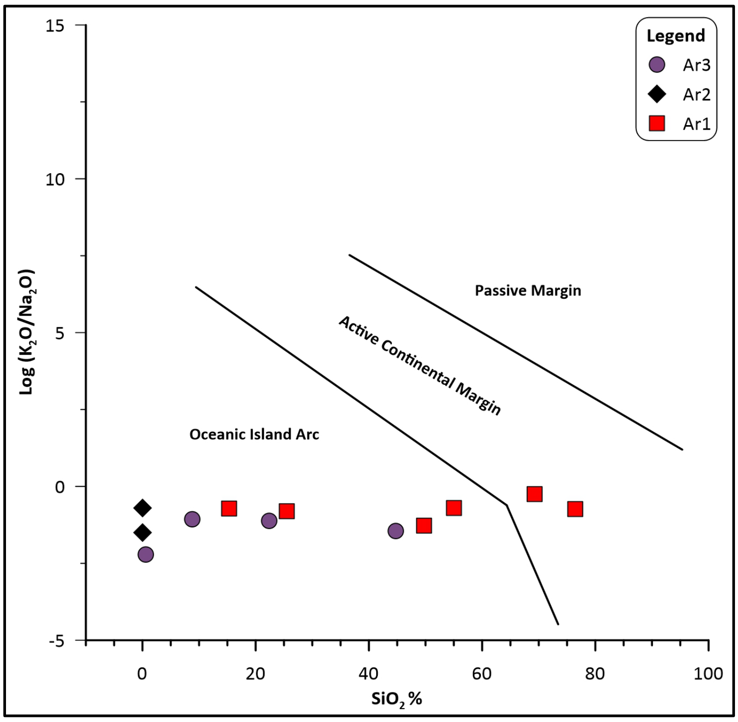

Figure 15. Presentation of the discriminant Log (K_2O/Na_2O) versus SiO_2 diagram of samples from the Ader Doutchi Formation in the Akoumoutt area. This **Figure** demonstrates the provenance of sediments from an oceanic island arc and an active continental margin, as indicated by the diagram proposed by Nesbitt & Young (1982).

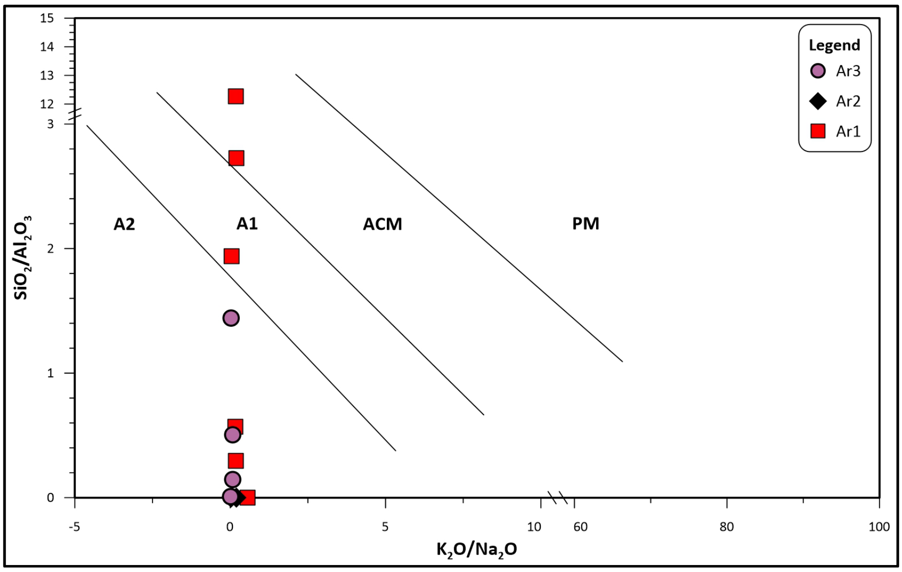

Figure 16. Tectonic discrimination diagram SiO_2/Al_2O_3 vs K_2O/Na_2O for sedimentary rocks after Maynard et al. (1982). ACM = active continental margin; PM = passive margin; A1 = arc setting, basaltic and andesitic detritus; A2 = evolved arc setting, felsic plutonic detritus.

5. Conclusion

A complete analysis of sedimentological facies, in conjunction with substantial geochemical data (XRF), has yielded crucial insights into the source of sedimentary rocks, the tectonic setting, and the paleoalterations that led to the deposition of Ypresian to Miocene in age deposits within the northern region of the Ader Doutchi sub-basin. This methodological approach has elucidated the sedimentary and tectonic processes that have shaped this region. Geochemical analyses revealed the presence of ferruginous clays and ferruginous sandstones. The petrographic and geochemical characteristics of these samples provide evidence that supports their mafic and felsic origins. The sediments may have been sourced from the terranes of the Touareg shield, which includes the Aïr, Adrar des Iforas, and Hoggar regions. Geochemical analyses revealed that the ferruginous mudstones and ferruginous sandstones originate essentially from an oceanic island arc, and more specifically from an evolved arc with felsic plutonic debris. This study revealed that certain sediments originated from an active continental margin. The Ct^1 sediments observed in the Akoumoutt section are essentially mature and have undergone significant alteration, ranging from strong to moderate. This alteration is attributable to an environment characterized by altering wet and dry cycles, with a tendency towards aridification. The Ypresian to Miocene in age deposits of the Ader Doutchi sub-basin contain substantial concentrations of pyrite, which frequently undergoes transformation into siderite. The presence of termitic tubing is also occasionally notable. The depositional environment of the Ader Doutchi Formation in the Akoumoutt sector fluctuated between anoxic and oxic states. Integrating sedimentological and geochemical data indicates that the Ct^1 deposits formed in marine, marginal littoral, and continental environments.

Conflicts of Interest

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

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