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Geochemical Exploration of Sediments in the Toumodi Region: Origin of Metasediments, Geological Dynamics, and Perspectives for Regional Geological History

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Abstract

The region of Toumodi, located in the heart of the West African Craton, is renowned for its geological complexity. This geochemical study delves into the origin of siliciclastic sediments and the geodynamic context of their formation. The study reveals that Toumodi's sediments exhibit an intriguing mineralogical composition, with indications of a dual source of parent rocks, one rich in quartz and the other poor in quartz. Furthermore, geochemical analysis highlights a variation in sediment maturity from west to east, indicating the coexistence of distinct geotectonic environments in the region. In the eastern part of the Toumodi region, a passive margin is defined characterized by sediments with an abundance of quartz, while to the west, an active margin is observed with sediments having a lower quartz content. This arrangement suggests the presence of a potential suture zone in the region. This geological complexity underscores the importance of further research to better understand the origin of sediments and the processes that have shaped them. Moreover, this study sheds new light on the fascinating geology of Toumodi, but many questions remain to be explored.

Keywords

Toumodi, Birimian, Siliciclastic Sediments, Sediment Maturity

1. Introduction

Geological regions often house a wealth of crucial information for understanding the evolution of our planet, documenting billions of years of complex geological processes. One of these captivating regions is Toumodi, located in the southern part of the West African Craton and belonging to the Paleoproterozoic domain. The diversity of rock formations is truly impressive [1] [2] [3], and the succession of geological events shapes their structure in a complex way [4] [5] [6] [7] [8]. In addition to these remarks, what distinguishes this context above all is the vast range of mineralization systems [2] [3] [5]. The geological characteristics of this region have long captured the interest of the scientific community. The Toumodi region is the result of its rich geological history of events, volcanic activity, tectonic deformations, a variety of rock types, and mineral resources such as gold. The sedimentary, magmatic, metamorphic, and tectonic processes that have shaped these rocks over time serve as windows into the geological history of the region. This complexity offers numerous opportunities for geological studies to better understand the Earth's history in this specific area. Scientists have dedicated efforts to unravel the mysteries of the complexity of this region and have highlighted its exceptional potential. Within the Toumodi region, two bands of sediments are present: one at the extreme east along the Kan Fault, measuring 1 to 2 km thick and covering the locality of North Lomo, and the other, more central, with a thickness of up to 10 km. These sediments, containing the imprints of transport and deposition processes through the ages, prove particularly intriguing. However, despite their importance in geological history, sediments have been relatively understudied; they await exploration to reveal their secrets and provide essential clues about their origin and the setting that governed their formation. The primary objective of this study is to explore these sediments using a geochemical approach to address fundamental questions about their source and the environmental context of their formation. This approach will contribute to completing the geological puzzle of the Toumodi region, offering promising perspectives for the exploration of natural resources in this area.

2. Geological Context

The West African Craton is a major geological region which includes two important ridges, namely the Réguibat ridge to the north and the Man ridge to the south. These two ridges are separated by two distinct geological features: the Taoudéni basin, which presents a variety of ages ranging from the Neoproterozoic to the Devonian, and the geological windows of Kédougou-Kéniéba and Kayes, which date back to the Paleoproterozoic [9] [10] [11]. Regarding the Man Ridge, it is characterized by a mosaic of geological formations. In its eastern part, the Man Ridge presents older terrains, of Archaean age, as evidenced by the results of previous research [12] [13] [14] (**Figure 1**). On the other hand, in its western part, we find the Baoulé-Mossi domain to which the Toumodi-Fetekro-Oumé greenstone belt belongs, is mainly made up of various rocks of tholeiitic to calc-alkaline affinity of Paleoproterozoic age [15]-[26]. The geology of the Toumodi-Fètêkro-Oumé greenstone blet, where our study area is located, is made up of varied rocks, little or moderately deformed. We note the presence of volcanics (lava, intrusion and volcaniclastics), metasediments, metapyroxenolites, metagabbros, orthoschists or calcoschists deriving from andesitic to basaltic lavas, dolerites, tuffs, metarhyolites, metadacites and associated conglomerates [27] (**Figure 2**). The metamorphism is green schist to amphibolite type. There are also some very small granitoid massifs [3] [4] [6] [28]-[33]. This variety of rocks and metamorphic processes is evidence of the geological complexity of the study area.

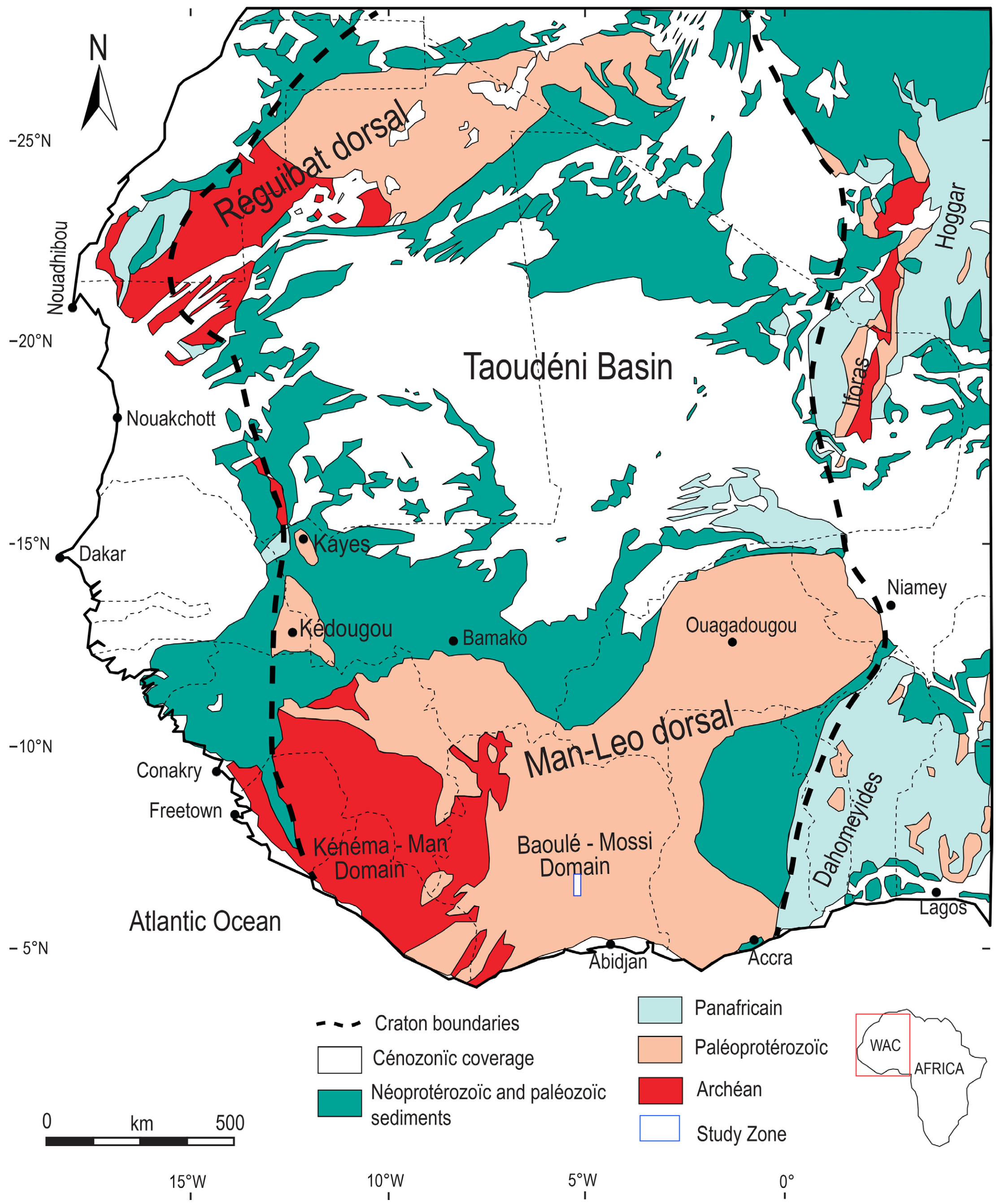

Figure 1. Synthetic geological map of the West African craton [34].

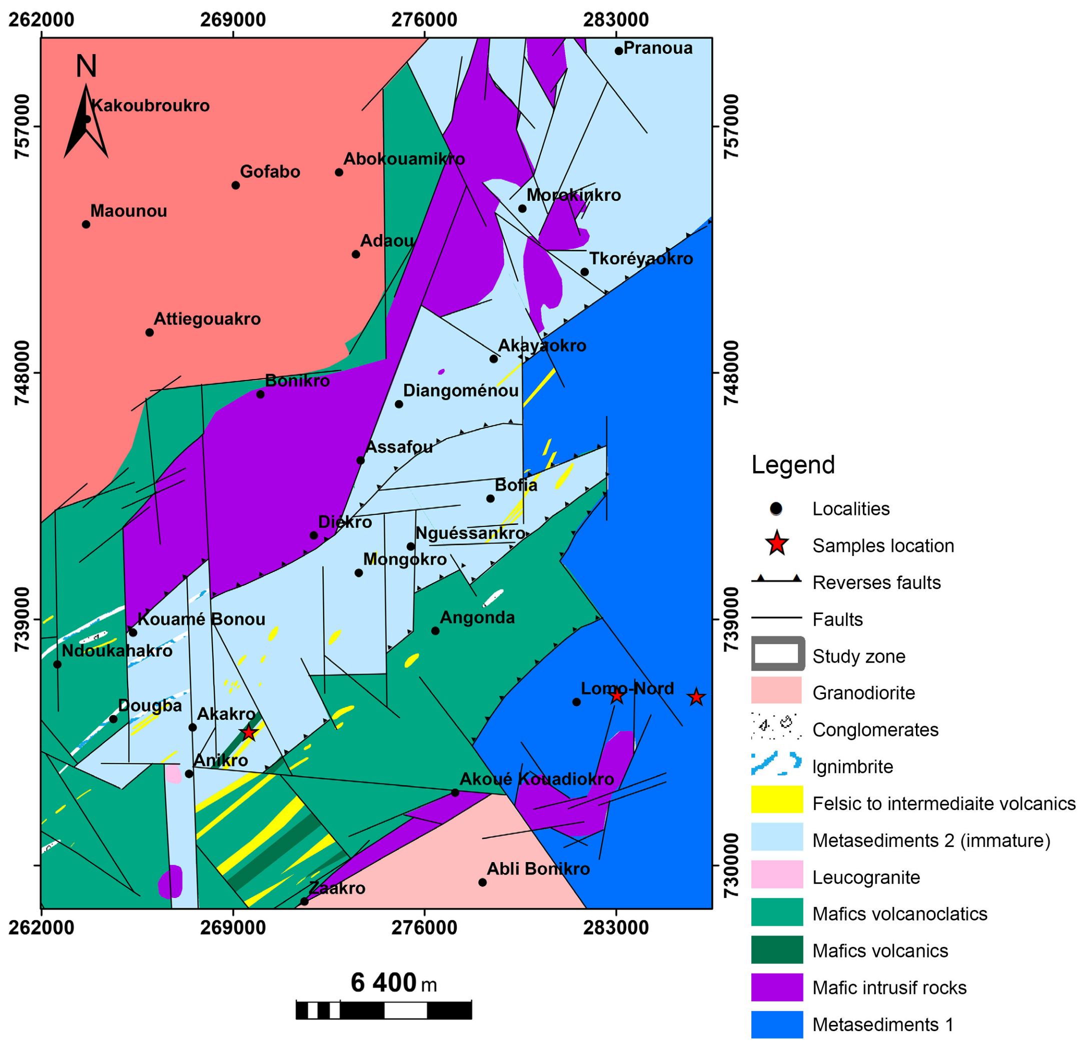

Figure 2. Simplified geological map of the central part of the TFO greenstone belt according to (this paper). Modified.

3. Material and Methods

The geochemical approach to siliciclastic sediments in the Toumodi region is based on a rigorous methodology consisting of several stages. Initially, sample collection took place in various representative zones of the region. Out of the initially collected six samples, only four were chosen for laboratory analysis. Moreover, only three sets of analysis results were presented due to the high silicification rate in one of the samples. This selection was guided by the aim of maximizing geological representativity by excluding samples exhibiting alterations, especially silicification. The selected samples were transported to the Bureau Veritas Ltd Analysis Laboratory, where they underwent preparatory steps, including drying, sieving, and grinding to achieve a consistent grain size.

Subsequently, advanced geochemical techniques were employed, such as X-ray fluorescence spectrometry (XRF) for analyzing the primary and secondary composition of the samples, and high-frequency induced plasma mass spectrometry

(ICP-MS) for examining elements at low concentrations and isotopes. Interpretation of the geochemical analysis results in **Table 1** was conducted in consideration of the specific study objectives and with reference to existing geochemical literature. Given the complexity of ancient terrains, where both superficial and endogenous processes like hydrothermalism, metamorphism, and metasomatism can alter the geochemical signature of rocks, a common approach involved using multiple adapted classification diagrams. This method facilitated achieving an interpretative balance that best reflected the region's geology, addressing challenges associated with geochemical data analysis in complex geological contexts.

Table 1. Multi-element analysis (major and trace elements) of the Toumodi's sediments.

Elements (% weigth)	TV48	TV65	TV58
SiO_2	78.44	73.77	55.51
Al_2O_3	11.69	13.38	19.36
Fe_2O_3	2.3	4.03	12.38
CaO	1.54	0.25	2.09
MgO	0.33	2.53	0.89
Na_2O	5.01	0.53	2.57
K_2O	0.2	2.08	1.38
MnO	0.04	0.05	0.01
TiO_2	0.14	0.26	1.29
P_2O_5	0.03	0.13	1.68
Cr_2O_3	0	0	0.09
LOI	0.28	2.98	2.74
SO_3	0	0	0
TOT	**100**	**99.99**	**99.99**
Ba	43	402	2634
Be	2	1	2
Co	2	5.5	17.2
Cs	0.1	0.9	0.9
Ga	12.3	13.9	18.8
Hf	3.8	5.1	5.1
Nb	10.9	6.9	8.7
Rb	4.7	40.3	38.8
Sn	1	<1	<1
Sr	136.3	152.7	933.1

Continued

Ta	0.7	0.5	0.6
Th	7.1	6	17.4
U	2	2.1	1.2
V	<8	14	146
W	1	<0.5	0.6
Zr	133.7	200.4	212
Y	26.2	17	35.7
La	36.4	31.9	172.9
Ce	69.9	63.6	365
Pr	8.42	7.42	45.63
Nd	29.6	26.3	171.3
Sm	5.2	4.3	25.3
Eu	0.53	0.93	6.07
Gd	4.64	3.69	15.57
Tb	0.68	0.54	1.64
Dy	4.09	3.13	7.23
Ho	0.98	0.66	1.11
Er	3.06	1.81	2.9
Tm	0.47	0.28	0.39
Yb	3.19	1.88	2.48
Lu	0.5	0.33	0.36
Mo	0.6	0.3	<0.1
Cu	3.6	9.6	10.5
Pb	5.5	2.7	5.4
Zn	26	57	79
Ni	7	11.6	190.5
As	<0.5	1.4	6.1
Cd	<0.1	<0.1	<0.1
Sb	0.1	<0.1	0.6
Bi	1.3	<0.1	0.1
Hg	<0.01	<0.01	<0.01
Tl	<0.1	<0.1	<0.1
Se	<0.5	<0.5	<0.5

4. Results

4.1. Detailed Description of Sediment Samples from the Toumodi Region

Sample TV-48 was collected approximately 1.5 kilometers east of the village of

Lomo Nord. Visually, it appears as dark gray facies with well-defined surface laminations, exhibiting slight alteration that imparts a whitish hue (**Figure 3A**). The rock displays a conchoidal fracture, indicating a particularly hard texture. Its geological context is intriguing, situated in close proximity to gabbroic intrusions and other recent sediments, suggesting a complex history of geological interactions. Collected northeast of Akakro N'zikpri, sample TV-58 is associated with pelitic metasediments extending from the western boundary of the village of Lomo Nord to N'doukahakro (**Figure 3B**). The visual appearance is characterized by a dark gray color, featuring small light gray spots resembling distinctive nodules of varying shapes and sizes. Notably, this sample occasionally interacts with acid volcanics located at Assafou and Anikro, adding complexity to its geological context. The thickness of this facies and its geological associations contribute to its intriguing features. Derived from the dry bed of a stream, likely a tributary of the Kan River, sample TV-65 exhibits an overall brown color, occasionally transitioning to darker shades (**Figure 3C**). The moderately fine grain size in this sample is attributed to exposure to weathering processes. Collected from a streambed, this sample provides valuable information about its depositional environment and dynamic history. In summary, the detailed descriptions of samples TV-48, TV-58, and TV-65 offer a comprehensive overview of their visual characteristics and geological contexts, contributing to a more thorough understanding of the geological evolution of the Toumodi region and the complex processes shaping its landscape.

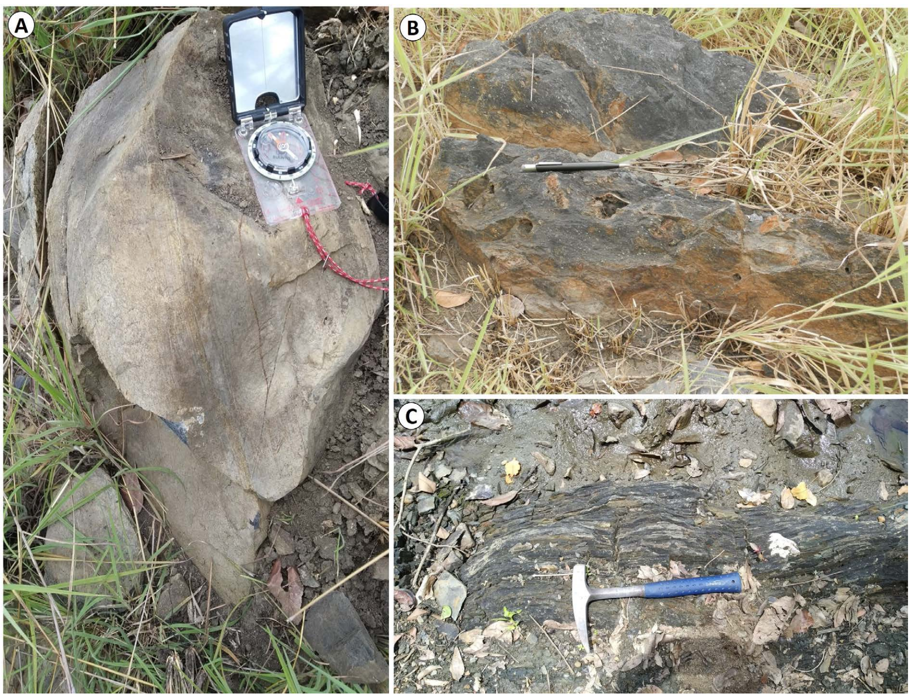

Figure 3. (A) Grauwackeous metasediments east of Lomo; (B) Grauwackeous metasediments northeast of Akakro N'Zikpri; (C) Silty metasediments in the bed of a stream at the extreme east of Lomo Nord.

4.2. Origin of Metasediments and Tectonic Setting

The ternary diagram presented in **Figure 4A** serves as a crucial tool for unraveling the intricacies of sedimentary rock composition in the Toumodi region. The dominance of sodic sandstone, as evidenced by the diagram, highlights a prevailing geological feature. However, the unique characteristics of sample TV-65, resembling magnesian to potassic sandstone, introduce a fascinating dimension of geological diversity, suggesting distinct sedimentary processes or sources in this specific location. Moving on to the assessment of mineralogical maturity using the Na_2O vs K_2O ratio (**Figure 4B**), the nuanced insights into quartz proportions within the rocks provide valuable information. The confirmation of their siliciclastic nature is expected, but the revelation of different sources, some rich and others deficient in quartz, adds a layer of complexity to the geological history of the region. This insight prompts questions about the environmental conditions and processes that led to such variations in quartz content. The substitution of scandium (Sc) with cobalt (Co) in the diagram of **Figure 4C** shows the particularly influencing sample TV-58 signifies an important aspect of geochemical maturity. The indication that this rock has not reached a stage of geochemical maturity opens avenues for speculation on ongoing geological processes and variations in rock composition within different zones of the Toumodi region. This observation may be linked to the local geological context, and further investigations could shed light on the factors influencing this particular rock's development. Transitioning to the Ce vs La/Yb diagram (**Figure 4D**), the confirmation of maturity in samples TV-65 and TV-48 aligns with the notion of tectonically stable environments, such as passive margins. In contrast, the immature nature of sample TV-58, characterized by a La value exceeding 50 ppm, suggests a link to a tectonically unstable environment, possibly an active margin. This distinction in geochemical maturity provides not only a snapshot of the current state but also a window into the past tectonic processes that have shaped the region. The La/Th vs Hf diagram (**Figure 4E**) delves deeper into the sediment source, indicating an intermediate source for the sediments in the TFO region. The significant contribution from various sources for sample TV-58 suggests a complex interplay of geological processes in this specific location. This complexity adds another layer to the regional geological history, hinting at diverse sedimentation patterns and potential interactions between different geological domains. Examining the rare earth element (REE) spectra unveils the specific enrichment patterns for each metasediment type. The negative europium (Eu) anomaly in TV-48 and positive anomalies in Ti, V, Cr, Fe, Ni, Sr, and HREE for TV-58 offer subtle insights into the geochemical evolution and specific sources of these materials. These anomalies are akin to geochemical fingerprints that narrate a story of the geological processes shaping the region over time. Lastly, the analysis of geotectonic positions through **Figure 5** and **Figure 6** provides intriguing perspectives. The placement of samples TV-65 and TV-48 within the domain of passive margins suggests a relatively stable tectonic environment. In contrast, the peripheral location of sample TV-58 within the Mobile

Collisional Plate (MCP) geotectonic domain indicates a potential interaction with a more dynamic geological environment. This interaction involves tectonic movements and collisional processes, contributing to the geological complexity observed in the Toumodi region. In summary, this comprehensive analysis of geochemical data goes beyond mere identification of rock types; it unravels a narrative of the geological evolution of the Toumodi region. Each facet, from mineralogy to geotectonics, contributes a piece to the puzzle, forming a holistic understanding of the geological complexity. These detailed insights not only deepen our comprehension of the region but also lay the groundwork for future investigations aimed at uncovering the specific mechanisms that have shaped Toumodi's geological history.

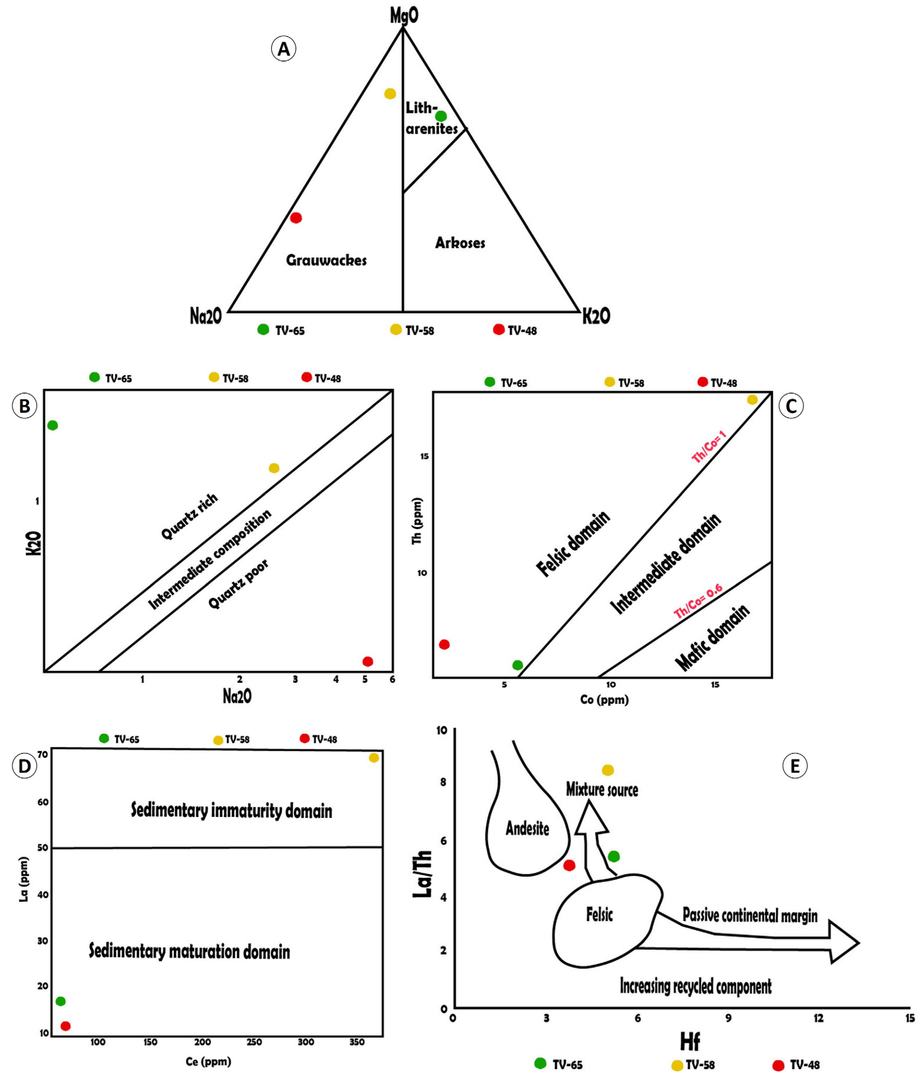

Figure 4. Origin and provenance of the sediments of the central part of the TFO furrow: (A) Ternary diagram of [35]; (B) Na_2O vs K_2O binary diagram; (C) Diagram of Th versus Co for sediment samples, the ratio Th/Co = 1 is that of the upper continental crust (UCC) data from [36] modified; (D) Ce vs La diagram from [37] showing sediment maturity; (E) Binary diagram La/Th vs Hf modified from [38] applied to metasediments showing the presence of sources of intermediary composition and mixing.

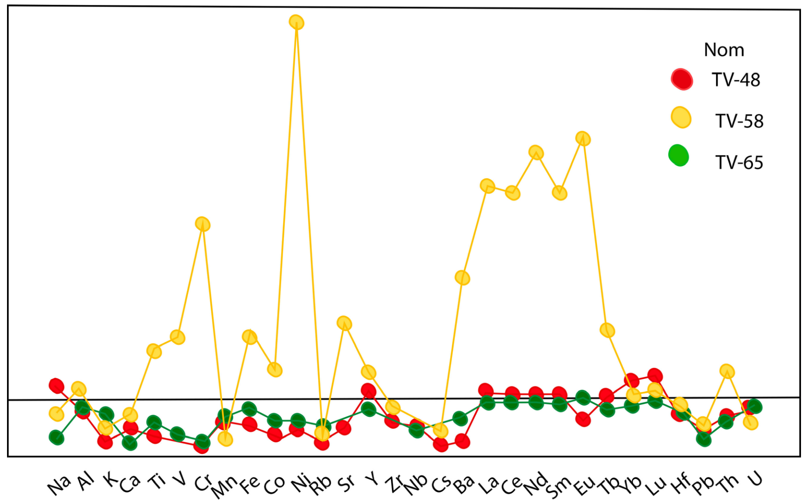

Figure 5. Diagramme multiéléments appliqué aux échantillons de sédiments [39].

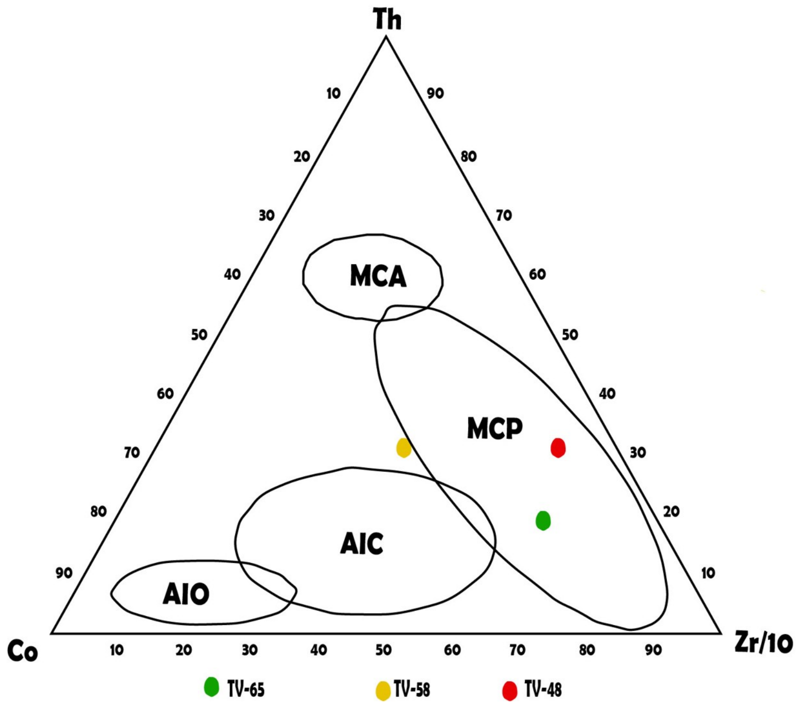

Figure 6. Diagramme ternaire Th-Co-Zr 10 montrant la discrimination géotectonique de [40] [41] appliqué aux métasédiments. MCA: marge continentale active; MCP: marge continentale passive; AIO: arc des îles océaniques; AIC: arc des iles continentales.

5. Discussion

The sedimentary composition of the central part of the TFO (Toumodi-Fetekro-Oumé) greenstone belt has sparked significant geological interest due to its complexity, offering valuable insights into the regional geological history. This region is primarily characterized by the prevalence of greywackes and litharenites, sedimentary rocks known for their mixture of sand, silt, and clay particles with angular to subangular grains. In-depth studies conducted by [3] [42], and [33] have consistently identified these sedimentary formations in the TFO volcano-sedimentary greenstone belt trough. Additionally, similar sedimentary features have been observed in the neighboring Comoé basin, as reported by [43] [44] [45], and [46], suggesting shared sedimentary continuity and a potential geological connection between the formations in these two areas. One fascinating aspect revealed by the sediment composition is the proposition of a dual source of sediments in the Toumodi region. According to this hypothesis, the sediments originate from two distinct types of source rocks. The first source, rich in quartz (silica)—a mineral commonly associated with granitic rocks in the continental crust. The second source, although lacking quartz (silica), exhibits a felsic character, suggesting an intermediate composition, likely a granodioritic rock, and potentially associated with mafic or ultramafic rocks such as gabbros. This interpretation aligns with the observations of [3] but challenges certain conclusions drawn from the Comoé basin by [44] [45], and [46], who suggested that the metasediments in that basin originated from granitic and gabbroic rocks. Despite variations in analytical techniques and geochemical markers, the convergence of results underscores the complex nature of sediment provenance studies, emphasizing the need for meticulous consideration of geological context and geochemical criteria. Moving to another significant observation, there is a distinct variation in sediment maturity from west to east in the Toumodi region. Sediments in the eastern part exhibit higher maturity than those in the western part. Sediment maturity serves as an indicator of the degree of sediment processing, suggesting a dynamic geological framework where sediments underwent various processes during their transport from west to east. These processes include weathering, erosion, transport, and sedimentation, contributing to the observed maturity gradient. The west-to-east variation in sediment maturity reflects a complex interaction of geological factors and suggests the coexistence of distinct tectonic environments in the same region. This observation aligns with the interpretations of [45] [46] [47], and [48]. Understanding how sediments could originate from two distinct tectonic environments within the same area remains a geological challenge. [8], in his explanation of the geodynamics of the Toumodi region, highlighted two types of volcanic arcs, one evolving and the other less evolving. These sediments could represent major elements of each of these arcs, suggesting a dynamic geological history. Another plausible hypothesis is that these environments were initially separated and subsequently brought together due to tectonic movements, leading to a mixture of sediments with different origins. This scenario implies that the Ivorian Birimian would be composed of small juxtaposed basins that came together during geological tightening. These complex geological processes contribute to the intriguing and intricate geological history of the Toumodi region from a scientific perspective.

6. Conclusion

The geochemical study of sediments in the Toumodi region offers intriguing perspectives for understanding the complex geological evolution of this area. Diverse geological features and sedimentary, magmatic, metamorphic, and tectonic processes have shaped the region over time, creating geological diversity that has captured the attention of the scientific community. The analysis of samples TV-48, TV-58, and TV-65 has provided crucial insights into the origin of metasediments in the region. The results indicate a dual sediment source, suggesting contributions from both quartz-rich granitic rocks and potentially granodioritic intermediate rocks. This discovery aligns with other research in the region, highlighting the complexity of sediment provenance studies. The variation in sediment maturity from west to east in the Toumodi region suggests dynamic and complex sedimentary processes. The observed differences may result from tectonic movements, environmental changes, or a combination of geological factors, reinforcing the notion of dynamic geological interaction within the region. Ultimately, this study contributes to illuminating the geological history of the Toumodi region using a comprehensive geochemical approach. The obtained results provide a solid foundation for future research and contribute to the overall understanding of geological processes at play in this specific region of the West African Craton. The geological richness of Toumodi continues to inspire scientific curiosity and offers fertile ground for future discoveries.

Conflicts of Interest

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

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