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Sediment Provenance, Geodynamic Evolution and Metallogenic Significance of Sandstones and Magmatic Intrusions from the Eastern Congo Basin, Democratic Republic of the Congo

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Abstract

Purpose: This study investigates the geochemistry of sandstones and associated magmatic intrusions from the eastern Congo Basin to constrain sediment provenance, weathering intensity, tectonic setting, and metallogenic potential.

Methodology: Representative samples of sandstones, granites, granodiorites, and gabbros were collected from the Wanie-Rukula area and analyzed using X-ray fluorescence spectrometry (XRF). Major and trace element compositions were interpreted through weathering indices, particularly the Chemical Index of Alteration (CIA), provenance and tectonic discrimination diagrams, Clarke-normalized enrichment factors, correlation analysis, and principal component analysis. The integration of geochemical, petrographic, and field observations enabled a comprehensive assessment of sedimentary and magmatic evolution.

Findings: The results indicate that the sandstones were predominantly derived from felsic to intermediate continental source rocks, mainly granites and granodiorites. CIA values reveal moderate to intense chemical weathering consistent with prolonged alteration under humid tropical conditions. Geochemical discrimination diagrams suggest sediment contributions from both stable cratonic domains and tectonically active continental environments, reflecting a complex provenance history. The intrusive rocks record multiple stages of magmatic differentiation involving gabbroic, granodioritic, and granitic facies. Trace-element distributions reveal significant enrichments in Fe, Ag, Sb, Au, Mo, and W, highlighting the influence of magmatic-hydrothermal processes and indicating localized metallogenic anomalies within the study area.

Unique Contribution to Theory, Practice and Policy: This study provides new geochemical evidence on the provenance of sedimentary deposits, the evolution of magmatic systems, and the metallogenic potential of the eastern Congo Basin. The findings contribute to the understanding of crustal evolution and intracratonic basin development in Central Africa. From a practical perspective, the identified geochemical anomalies constitute valuable indicators for future mineral exploration programs. The study also provides a scientific basis for geological mapping, natural resource assessment, and sustainable management of mineral resources in the Democratic Republic of the Congo.

Keywords: *Congo Basin, Geochemistry, Sandstone Provenance, Chemical Weathering, Magmatic Intrusions, Metallogenic Potential*

JEL Codes: *Q24, Q32, Q38, O13*

1. Introduction

The Congo Basin is one of the world's largest intracratonic sedimentary basins and constitutes a key geological archive for reconstructing the tectonic, sedimentary, and paleoclimatic evolution of Central Africa (Kadima et al., 2011; Delpomdor et al., 2021; Guillocheau et al., 2023). Developed on the Precambrian Congo Craton, the basin preserves a long history of subsidence, continental sedimentation, and episodic tectonic reactivation that shaped its present-day architecture (Kadima et al., 2011; Delpomdor et al., 2021). Despite its geodynamic significance, several sectors of the basin, particularly its eastern margin, remain poorly documented, and the relationships between sedimentary formations and associated magmatic intrusions are still insufficiently understood.

The Ubundu region, located in Tshopo Province, Democratic Republic of the Congo, is characterized by extensive sandstone formations locally associated with granitoid and mafic intrusions. These lithological assemblages provide valuable records for reconstructing the geological evolution of the eastern Congo Basin. Sandstones preserve information on source-rock composition, weathering history, sediment transport, and depositional environments, whereas intrusive rocks provide insights into magma evolution, crustal differentiation, and tectonomagmatic processes (Gill, 2010; Winter, 2010; Cai et al., 2022; Fan et al., 2024).

Geochemical investigations of sedimentary rocks are widely recognized as robust tools for determining sediment provenance, evaluating source-area weathering, and reconstructing tectonic settings (Taylor & McLennan, 1985; McLennan et al., 1993; Cai et al., 2022; Luo et al., 2025). Major- and trace-element compositions generally preserve the geochemical signatures of their parent rocks and therefore provide reliable indicators of felsic, intermediate, or mafic provenance. Likewise, the Chemical Index of Alteration (CIA), originally proposed by Nesbitt and Young (1982), remains one of the most widely applied indices for assessing chemical weathering intensity and inferring paleoclimatic conditions, as confirmed by numerous recent studies (Cai et al., 2022; Fan et al., 2024).

Similarly, the geochemistry of igneous rocks provides essential information on magma evolution, fractional crystallization, crustal contamination, and tectonic environments of emplacement. Variations in major and trace elements also help identify metallogenic signatures associated with magmatic-hydrothermal systems. Recent studies have shown that enrichments in elements such as Au, Ag, Sb, Mo, and W commonly reflect evolved magmatic systems and hydrothermal fluid circulation associated with economically significant mineralization (Richards, 2018; Hou et al., 2021; Deng et al., 2023).

Although sandstone formations and magmatic intrusions are well exposed in the Ubundu area, integrated geochemical investigations remain scarce. Existing studies provide only fragmented information and do not adequately constrain sediment provenance, weathering intensity, tectonic evolution, magmatic differentiation, and associated metallogenic processes. This knowledge gap

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limits a comprehensive understanding of the geological evolution of the eastern Congo Basin and hinders accurate assessment of its mineral resource potential.

Accordingly, this study characterizes the geochemical composition of sandstones and associated magmatic intrusions from the Ubundu region to constrain sediment provenance, evaluate chemical weathering intensity, reconstruct the tectonic setting of sedimentation, and assess the petrogenetic and metallogenic significance of magmatic activity. It is hypothesized that the sandstones were predominantly derived from felsic to intermediate Precambrian basement rocks subjected to intense tropical weathering, whereas the intrusive rocks record multiple stages of magmatic differentiation accompanied by localized hydrothermal activity. By integrating major- and trace-element geochemistry, weathering indices, provenance and tectonic discrimination diagrams, and multivariate statistical analyses, this study provides new insights into the geological evolution of the eastern Congo Basin and its mineral exploration potential.

2. Literature review

2.1 Sandstone provenance and chemical weathering

The geochemistry of clastic sedimentary rocks provides valuable information on source-rock composition, weathering processes, and tectonic environments. Because major and trace elements are largely inherited from parent rocks, their distribution can be used to reconstruct sediment provenance and crustal evolution (Taylor & McLennan, 1985; McLennan et al., 1993). Major-element compositions are particularly useful for distinguishing sediments derived from felsic, intermediate, or mafic source rocks, while trace elements such as La, Th, and Sc provide reliable indicators of provenance because of their relative immobility during weathering and diagenesis (Roser & Korsch, 1988).

Chemical weathering strongly influences sediment composition before deposition. The Chemical Index of Alteration (CIA) proposed by Nesbitt and Young (1982) is widely used to evaluate the degree of weathering experienced by source materials. Low CIA values indicate limited alteration, whereas high values reflect intense chemical weathering and progressive depletion of mobile elements such as Ca, Na, and K. In tropical regions, elevated CIA values are commonly associated with prolonged weathering under humid climatic conditions (Harnois, 1988).

2.2 Geochemical indicators of tectonic setting

Geochemical discrimination diagrams have become important tools for reconstructing the tectonic environments of sedimentary basins. Major-element and trace-element approaches allow the distinction between sediments derived from stable continental areas, active continental margins, and magmatic arcs (Roser & Korsch, 1986; Bhatia & Crook, 1986). Among the most widely used methods, the La–Th–Sc ternary diagram provides valuable constraints on sediment source regions and tectonic settings because these elements are relatively resistant to post-depositional modification (McLennan et al., 1993).

The Congo Basin represents a major intracratonic sedimentary basin developed on the Precambrian Congo Craton. Although generally considered tectonically stable, several studies suggest that parts of the basin were influenced by episodic tectonic reactivation, which may have affected sediment supply and basin evolution (Cahen et al., 1984; Kadima et al., 2011). Geochemical investigations therefore provide an effective means of evaluating the relative influence of stable cratonic and tectonically active source regions.

2.3 Geochemistry of magmatic intrusions and metallogenic significance

The geochemistry of intrusive rocks is fundamental for understanding magma evolution, crustal processes, and mineralization. Granites, granodiorites, and gabbros commonly represent different stages of magmatic differentiation and may record multiple episodes of crustal evolution (Rollinson, 1993; Winter, 2010). Variations in major and trace element compositions can reveal processes such as fractional crystallization, magma mixing, and crustal contamination.

Trace-element enrichments are also important indicators of metallogenic processes. Elements such as Au, Ag, Sb, Mo, and W are frequently associated with hydrothermal systems related to evolved magmatic intrusions (Pirajno, 2009; Robb, 2005). Their anomalous concentrations may indicate fluid circulation and metal remobilization during late stages of magmatic evolution. Consequently, integrated geochemical studies of sedimentary and intrusive rocks provide a robust framework for reconstructing basin evolution while simultaneously assessing mineral exploration potential.

Despite the geological importance of the eastern Congo Basin, integrated studies addressing sediment provenance, weathering history, magmatic evolution, and metallogenic implications remain scarce. The present research seeks to fill this gap by combining sedimentary and igneous geochemistry to better understand the geological evolution and mineral resource potential of the Ubundu region.

3. Materials and methods

3.1 Study area

The study was conducted in the Wanie-Rukula region and surrounding areas located within the Ubundu Territory, Tshopo Province, northeastern Democratic Republic of the Congo. The study area forms part of the eastern sector of the Congo Basin, one of the largest intracratonic sedimentary basins in Africa. The region is characterized by extensive sandstone formations locally associated with intrusive igneous bodies, including granites, granodiorites, and gabbros.

Geologically, the area lies on the Precambrian basement of the Congo Craton and records a complex history involving sedimentary deposition, tectonic reactivation, and magmatic emplacement. The tropical humid climate, marked by high rainfall and intense chemical weathering, strongly influences rock alteration processes and sediment production.

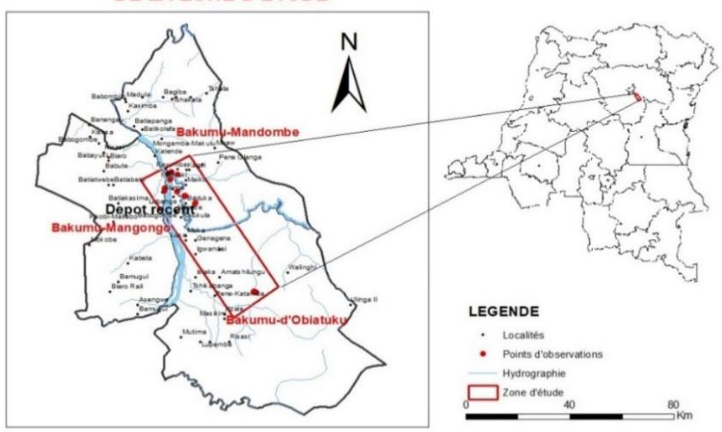

Figure 1: Location map of the study area showing sampling sites in the Wanie-Rukula region.

3.2 Field sampling and petrographic characterization

Field investigations were conducted in the Wanie-Rukula area to identify representative lithological units and collect fresh rock samples for petrographic and geochemical analyses. Sampling focused on both sedimentary and intrusive igneous formations exposed in natural outcrops and erosional surfaces. To minimize the effects of surface alteration, only the least-weathered portions of each outcrop were selected.

A total of 21 representative rock samples were collected, including 9 sandstone samples, 5 granite samples, 4 granodiorite samples, and 3 gabbro samples. These lithologies were selected because they constitute the principal geological units exposed within the study area and are considered representative of the sedimentary and magmatic evolution of the eastern Congo Basin.

For each sampling site, geographic coordinates were recorded using a handheld GPS receiver. Lithological descriptions, structural observations, mineralogical characteristics, and field relationships between sedimentary and intrusive units were systematically documented. Macroscopic petrographic observations were subsequently carried out to characterize mineral composition, grain size, texture, and alteration features prior to geochemical analysis.

3.3 Sample preparation and geochemical analyses

Rock samples were cleaned, air-dried, and mechanically crushed before laboratory preparation. Weathered surfaces and visibly altered fragments were removed to reduce contamination and analytical bias. The selected materials were pulverized to a homogeneous powder with a grain size of less than 75 µm.

Geochemical analyses were performed at the Centre de Recherches Géologiques et Minières (CRGM Laboratory) using X-ray fluorescence spectrometry (XRF). Major-element concentrations were determined and reported as oxide percentages (wt.%), whereas trace-element concentrations were expressed in parts per million (ppm).

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Analytical quality control was ensured through the use of certified reference materials, duplicate analyses, and routine instrument calibration. The analytical precision was generally better than ±2% for major elements and ±5% for trace elements. Detection limits varied according to the analyzed element and ranged from 0.001 wt.% for major oxides **to** 0.1–1 ppm for most trace elements.

The generated geochemical dataset was subsequently used to calculate weathering indices, evaluate sediment provenance, identify tectonic signatures, and assess the metallogenic potential of the investigated rocks.

Macroscopic petrographic observations were used to characterize mineralogical composition, grain size, texture, and alteration features. These observations provided the geological framework necessary for the interpretation of geochemical data.

Figure 2: Representative sandstone outcrops and sampling locations

Figure 3: Photographs of granite, granodiorite, and gabbro samples.

3.4 Geochemical indices and provenance analysis

The intensity of chemical weathering affecting the source rocks was evaluated using the Chemical Index of Alteration (CIA) proposed by Nesbitt and Young (1982):

$$CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$$

where all oxides are expressed on a molar basis and CaO^* represents calcium incorporated within silicate minerals.

CIA values were interpreted according to established weathering classifications, with low values indicating weak alteration and high values reflecting intense chemical weathering (Nesbitt & Young, 1982).

Sediment provenance was investigated using major-element discrimination diagrams and ternary geochemical plots, particularly the Al_2O_3–TiO_2–Fe_2O_3 system, which allows differentiation between felsic, intermediate, and mafic source rocks (Roser & Korsch, 1988).

Tectonic setting and sediment source environments were further assessed using the La–Th–Sc ternary discrimination diagram developed by Bhatia and Crook (1986). This approach enables discrimination among sediments derived from continental island arcs, active continental margins, and passive continental settings.

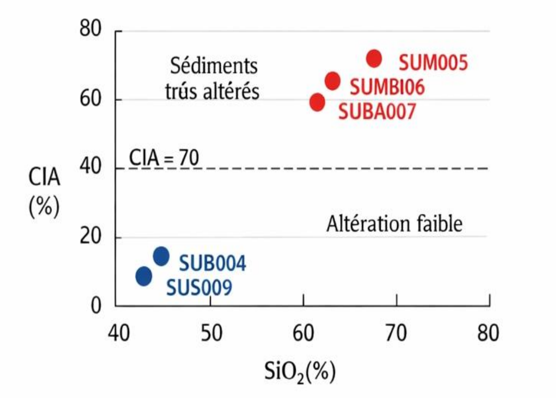

Figure 4: CIA versus SiO_2 weathering diagram

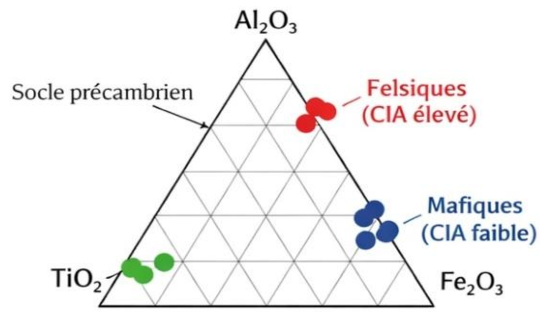

Figure 5: Al_2O_3–TiO_2–Fe_2O_3 provenance discrimination diagram

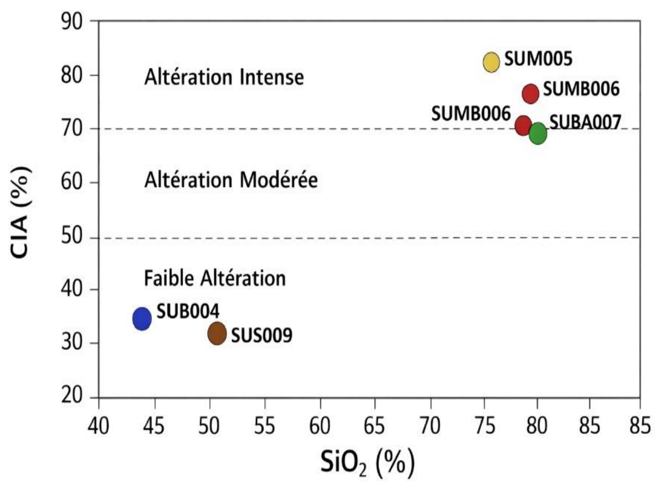

Figure 6: La–Th–Sc tectonic discrimination diagram

3.5 Trace element enrichment and metallogenic assessment

To evaluate potential metallogenic signatures, trace-element concentrations were normalized to Clarke values following the methodology proposed by Govett (1983). Normalization reduces lithological effects and facilitates the identification of anomalous enrichments associated with mineralizing processes.

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Enrichment factors were calculated for economically significant elements, including Au, Ag, As, Sb, Mo, W, Pb, Cu, and Zn. Particular attention was given to element associations commonly linked to magmatic-hydrothermal systems.

The spatial and geochemical distribution of anomalous elements was interpreted in relation to magmatic differentiation processes, hydrothermal fluid circulation, and regional geological controls.

Table 1: Descriptive statistics of major and trace elements

Element	Minimum	Maximum	Mean	Median	Standard Deviation	CV
Au	0.005	0.18	0.02833	0.015	0.04094	1.445
Ag	0.001	1.23	0.5043	0.22	0.5002	0.9918
As	0.005	0.046	0.02133	0.020	0.00987	0.4626
Co	0.005	0.44	0.1567	0.15	0.1175	0.7501
Cu	0.0042	0.596	0.06397	0.0292	0.1342	2.098
Cr	0.0021	0.021	0.01212	0.012	0.005098	0.4207
Fe	72.58	78.98	75.36	75.34	1.683	0.02234
Mo	0.50	3.00	1.06	0.525	0.798	0.7528
Ni	0.019	0.189	0.06261	0.049	0.04097	0.6543
Pb	0.010	0.47	0.145	0.095	0.1406	0.9693
Sb	0.25	2.00	0.5583	0.25	0.5219	0.9348
Sc	0.00025	0.0359	0.01373	0.0104	0.009162	0.6672
Sn	0.05	0.24	0.1144	0.12	0.06528	0.5704
Sr	0.00078	0.467	0.05353	0.004105	0.1209	2.258
V	0.00	0.7297	0.06318	0.0126	0.1728	2.736
W	0.75	1.84	1.217	1.15	0.3255	0.2674
Zn	0.011	0.35	0.07122	0.023	0.09689	1.360

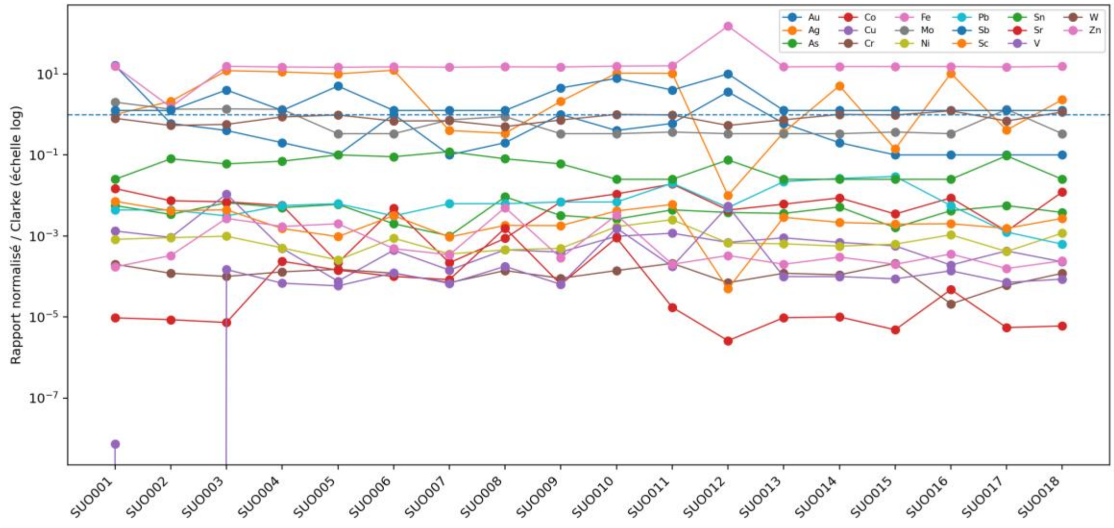

Figure 7: Clarke-normalized trace-element distribution patterns

3.6 Statistical analysis

Descriptive statistics, including minimum, maximum, mean, median, standard deviation, and coefficient of variation, were calculated for all analyzed elements. These parameters provided quantitative information on geochemical variability and element dispersion within the study area.

Pearson correlation analysis was performed to identify geochemical associations and possible common sources among elements. In addition, Principal Component Analysis (PCA) was applied to standardized geochemical data to reduce dimensionality and identify the major processes controlling geochemical variability.

Multivariate statistical analyses were conducted using standard geochemical data processing procedures widely employed in sedimentary and igneous geochemistry (Davis, 2002).

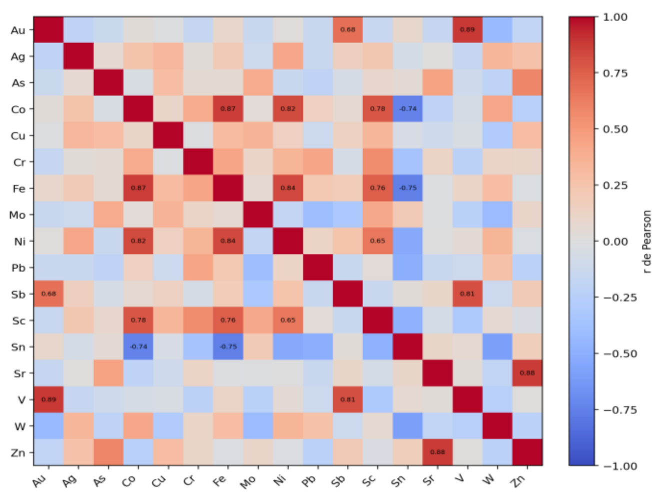

Figure 8: Correlation matrix heatmap

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4. RESULTS

4.1 Petrographic characteristics of the regional lithological facies

Field investigations identified four principal lithological facies within the Ubundu area: sandstone, granite, granodiorite, and gabbro. The granites are characterized by coarse-grained textures dominated by quartz, feldspars, and subordinate ferromagnesian minerals. Granodiorites display intermediate mineralogical compositions with abundant plagioclase and quartz, whereas gabbros are distinguished by their dark coloration and predominance of mafic minerals.

The spatial association between sedimentary formations and intrusive rocks indicates the coexistence of sedimentary and magmatic processes within the study area. The intrusive bodies occur as isolated outcrops crosscutting the regional sedimentary sequence.

Figure 9: Representative photographs of granite, granodiorite, and gabbro facies from the Ubundu area

4.2 Geochemistry of Ubundu sandstones

4.2.1 Chemical weathering intensity

The Chemical Index of Alteration (CIA) values exhibit substantial variability among the analyzed sandstone samples. CIA values range from low to high levels, indicating different degrees of chemical alteration within the sedimentary succession.

The relationship between CIA and SiO_2 contents reveals a progressive increase in alteration intensity with increasing silica enrichment. Samples characterized by relatively low CIA values are associated with less altered materials, whereas samples with elevated CIA values correspond to strongly weathered sediments.

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4.2.2 Major element distribution

The ternary Al_2O_3–TiO_2–Fe_2O_3 diagram shows a heterogeneous distribution of samples across the compositional field. Several samples are concentrated toward the Al_2O_3 apex, while others display enrichment in Fe_2O_3 or TiO_2.

The dispersion pattern reflects marked geochemical variability among the analyzed sandstones. The observed distribution suggests the contribution of multiple lithological components to the sedimentary assemblage.

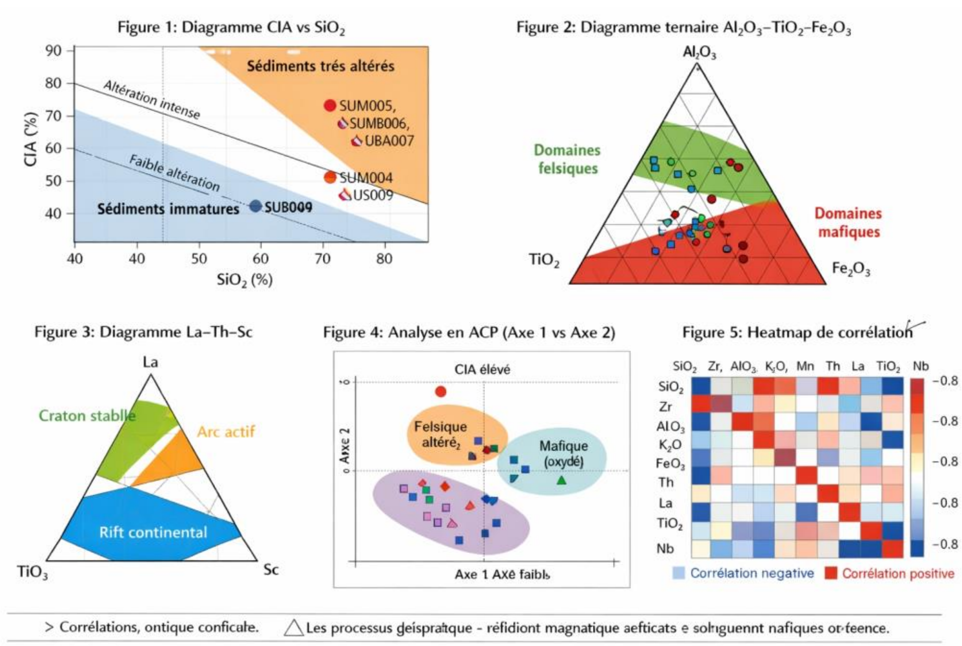

Figure 10: Al_2O_3–TiO_2–Fe_2O_3 ternary diagram

4.2.3 Tectonic discrimination patterns

The La–Th–Sc ternary plot reveals a wide dispersion of sandstone samples across the discrimination fields. Some samples plot within domains commonly associated with stable continental settings, whereas others occur within fields corresponding to more tectonically active environments.

The distribution pattern indicates considerable variability in the geochemical signatures recorded by the sedimentary units.

4.2.4 Multivariate geochemical relationships

Principal Component Analysis (PCA) reveals distinct groupings of samples according to their geochemical compositions. The first two principal components account for most of the total variance observed in the dataset.

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The correlation matrix highlights both positive and negative relationships among major oxides. Strong positive correlations are observed between selected elements, whereas inverse relationships characterize other geochemical associations.

4.3 Geochemistry of magmatic intrusions

4.3.1 Descriptive statistics of trace elements

Trace-element concentrations exhibit considerable variability among the analyzed intrusive rocks (Table 1). Iron (Fe) records the highest average concentrations, whereas gold (Au), arsenic (As), and scandium (Sc) occur at comparatively low levels.

The coefficients of variation indicate pronounced heterogeneity for several elements, including Cu, Sr, V, Au, Zn, and Ag, reflecting substantial differences among samples.

Table 2: Maximum enrichment factors and anomalous samples

Element	Sample with Maximum Value	Maximum Normalized Factor	Mean Normalized Value
Fe	SUO012	151.00	21.90
Ag	SUO006	12.30	5.04
Sb	SUO012	10.00	2.79
Au	SUO001	16.00	1.41
W	SUO016	1.23	0.811
Mo	SUO001	2.00	0.707
Sn	SUO007	0.12	0.0572
Pb	SUO015	0.0294	0.00906
Co	SUO011	0.0191	0.00681
As	SUO008	0.0092	0.00427

4.3.2 Clarke-Normalized Element Distribution

Normalized concentrations reveal marked differences among trace elements. Fe, Ag, Sb, Au, Mo, and W display the highest normalized values, whereas As, Co, and Pb generally remain at lower levels.

Several samples exhibit distinct enrichment patterns characterized by elevated normalized concentrations relative to background values.

4.3.3 Geochemical anomalies

The highest normalized Fe value is recorded in sample SUO012. Silver reaches its maximum enrichment in sample SUO006, whereas antimony displays its highest value in SUO012. Gold exhibits a pronounced anomaly in sample SUO001, while tungsten shows maximum enrichment in SUO016.

The distribution of anomalous values demonstrates substantial spatial variability among intrusive rock samples.

4.4 Synthesis of geochemical variability

The combined geochemical dataset highlights significant variability among both sandstone and intrusive rock samples. Major-element compositions reveal heterogeneous weathering and compositional trends within the sedimentary units, while trace-element distributions indicate marked differences among magmatic facies.

The multivariate analyses further emphasize the existence of distinct geochemical groups characterized by contrasting elemental associations. These patterns provide a comprehensive dataset for evaluating the geological evolution of the Ubundu region.

5. Discussion

5.1 Provenance of the Ubundu sandstones

The geochemical composition of the Ubundu sandstones provides important insights into the nature of the source rocks that supplied detrital material to the sedimentary basin. Major-element relationships and provenance discrimination diagrams indicate that the sediments were predominantly derived from felsic to intermediate continental sources. The enrichment in SiO_2 and Al_2O_3, combined with relatively low concentrations of ferromagnesian oxides, suggests substantial contributions from granitic and granodioritic rocks. Such geochemical signatures are characteristic of sediments generated through the weathering of mature continental crust and are commonly reported in intracratonic basins worldwide (Taylor & McLennan, 1985; Cullers, 2000).

The Al_2O_3–TiO_2–Fe_2O_3 ternary diagram further supports a mixed provenance involving both felsic and subordinate mafic components. Similar source-rock associations have been documented in several Proterozoic and Phanerozoic sedimentary basins where erosion affected heterogeneous crystalline basement complexes (Roser & Korsch, 1988; McLennan et al., 1993). The occurrence of minor mafic contributions may reflect localized erosion of basic intrusive bodies exposed within the regional basement or incorporated during successive sedimentary recycling episodes.

The La–Th–Sc tectonic discrimination diagram suggests that the sediments originated from source regions located within stable continental crust but influenced by tectonically active domains. This dual signature is consistent with the geological evolution of the Congo Craton, which experienced multiple episodes of crustal stabilization followed by localized tectonic reactivation during the Neoproterozoic and Phanerozoic (Batumike et al., 2009; Delpomdor et al., 2016). Consequently, the geochemical characteristics of the Ubundu sandstones preserve evidence of both long-term cratonic stability and episodic tectonic rejuvenation affecting sediment supply pathways.

5.2 Intensity of chemical weathering and paleoclimatic implications

The Chemical Index of Alteration (CIA) reveals moderate to intense chemical weathering of the source materials prior to sediment deposition. Elevated CIA values generally reflect progressive depletion of mobile cations such as Ca, Na and K during feldspar alteration and the relative enrichment of aluminum-bearing residual minerals (Nesbitt & Young, 1982). The weathering trends observed in the studied samples indicate extensive hydrolysis of plagioclase minerals and the development of clay-rich weathering profiles.

Such weathering conditions are commonly associated with humid tropical climates characterized by high rainfall and elevated temperatures that promote intense chemical alteration processes (Retallack, 2001). The present-day climatic conditions prevailing within the Congo Basin provide a modern analogue for these processes, although the geochemical data alone do not allow precise reconstruction of paleoclimatic parameters.

The progressive displacement of samples toward the Al-rich sector of the weathering diagrams suggests prolonged exposure of source rocks before sediment transport and deposition. Similar weathering signatures have been reported from tropical sedimentary systems across West and Central Africa, where prolonged chemical alteration significantly modifies sediment composition before basin accumulation (Nesbitt & Young, 1984; Condie et al., 2001).

The observed variability in CIA values further indicates that weathering intensity was not spatially uniform. Some samples retain relatively immature geochemical characteristics, suggesting shorter transport distances, rapid sedimentation rates, or contributions from freshly exposed source rocks. This heterogeneity likely reflects fluctuations in erosion dynamics and sediment routing systems operating during basin development.

5.3 Geodynamic significance of sedimentation in the Eastern Congo Basin

The geochemical evidence indicates that sedimentation occurred within a predominantly intracratonic setting influenced by localized tectonic activity. Intracratonic basins typically receive sediment derived from extensive continental erosion under relatively stable tectonic conditions, resulting in mature mineralogical and geochemical compositions (Einsele, 2000). The predominance of felsic signatures, together with advanced weathering indices, supports such an interpretation for the Ubundu sedimentary system.

However, the coexistence of tectonically active signatures revealed by trace-element discrimination diagrams suggests that sediment accumulation was not entirely disconnected from regional geodynamic processes. Previous studies have demonstrated that the eastern margin of the Congo Basin has experienced recurrent tectonic adjustments linked to continental-scale deformation episodes affecting Central Africa (Cahen et al., 1984; De Waele et al., 2008). These tectonic events may have generated renewed uplift of basement blocks, thereby enhancing erosion and modifying sediment provenance patterns.

The combined geochemical signatures therefore support a model in which sedimentation developed within a generally stable intracratonic environment periodically influenced by crustal reactivation. Such a framework reconciles the apparent contradiction between mature sediment composition and evidence for tectonic activity. Similar evolutionary scenarios have been proposed for other large intracontinental basins where sedimentary successions record both long-term stability and episodic tectonic disturbances (Allen & Allen, 2013).

5.4 Petrogenesis of the magmatic intrusions

The coexistence of granite, granodiorite and gabbro within the study area reveals a complex magmatic history involving multiple stages of magma evolution. The progressive transition from mafic to felsic lithologies is consistent with fractional crystallization processes operating within a differentiated magmatic system. During magmatic evolution, early crystallization of mafic minerals removes Fe, Mg and Ca from the melt, leading to progressive enrichment of residual liquids in silica and incompatible elements (Winter, 2010).

The geochemical contrasts observed between the intrusive facies suggest derivation from magmas that evolved under varying physicochemical conditions. The gabbroic rocks likely represent early mafic magma injections, whereas granodiorites and granites correspond to more evolved magmatic products generated through fractional crystallization and possible crustal contamination. Comparable intrusive associations have been described in numerous Precambrian terranes where repeated magmatic pulses accompanied crustal growth and reworking processes (Rollinson, 1993; Winter, 2010).

The emplacement of these intrusions after sediment deposition further indicates a post-sedimentary tectono-magmatic event. Such relationships imply that the geological evolution of the Ubundu region involved interactions between sedimentary basin development and subsequent magmatic activity, reflecting a dynamic crustal environment rather than prolonged tectonic quiescence.

5.5 Metallogenic implications

One of the most significant outcomes of this study concerns the identification of geochemical anomalies involving Au, Ag, Sb, Mo and W. These elements are widely recognized as indicators of hydrothermal activity and mineralizing processes associated with evolved magmatic systems (Robb, 2005). Their enrichment relative to average crustal abundances suggests that the Ubundu region may have undergone localized metallogenic processes capable of concentrating economically valuable metals.

The association between Au and Mo observed in certain samples is particularly noteworthy because it commonly characterizes hydrothermal systems genetically linked to felsic intrusive bodies. Gold-molybdenum associations have frequently been reported in intrusion-related mineral systems where mineralization develops during late-stage magmatic fluid circulation (Sillitoe, 2010). Similarly, elevated concentrations of Ag and Sb may indicate hydrothermal remobilization and precipitation under changing physicochemical conditions.

The anomalous enrichment of W provides additional evidence for highly evolved magmatic fluids. Tungsten mineralization is commonly associated with granitic intrusions enriched in incompatible elements and is frequently regarded as an indicator of advanced magmatic differentiation (Pirajno, 2009). The coexistence of Au, Ag, Sb, Mo and W anomalies therefore points toward a metallogenic environment potentially linked to differentiated felsic magmatism and hydrothermal fluid evolution.

Although the present dataset does not permit direct resource evaluation, the geochemical signatures identified here provide a strong basis for future mineral exploration. Detailed mineralogical investigations, isotopic analyses and structural studies would be required to determine the spatial extent, origin and economic significance of the observed anomalies.

5.6 Implications for the geological evolution of the Ubundu region

The integration of sedimentary and magmatic geochemical data reveals a coherent geological history characterized by three major stages. The first stage involved prolonged weathering of felsic to intermediate basement rocks under humid tropical conditions, generating mature sediments subsequently deposited within an intracratonic basin. The second stage was marked by episodic tectonic reactivation that influenced sediment supply and basin evolution. The third stage corresponded to the emplacement of differentiated magmatic intrusions accompanied by hydrothermal processes responsible for localized metal enrichment.

This evolutionary model highlights the close relationship between sedimentary processes, crustal dynamics and metallogenesis within the eastern Congo Basin. The study therefore contributes to a broader understanding of the geological evolution of Central Africa and demonstrates the value of integrated geochemical approaches for reconstructing complex basin histories.

5.7 Limitations of the study

Although this study provides valuable insights into the provenance of sandstones, magmatic evolution, and metallogenic potential of the Ubundu region, several limitations should be acknowledged. First, the number of analyzed samples remains relatively limited and may not fully capture the spatial geochemical variability of the entire study area. Additional sampling covering a broader range of lithological units would improve the representativeness of the dataset and strengthen regional interpretations.

Second, the present investigation relies primarily on major- and trace-element geochemistry. The absence of isotopic analyses, such as Sr–Nd–Pb or zircon U–Pb dating, restricts the ability to precisely constrain source-rock ages, magma sources, and crustal evolution processes. Such approaches would provide more robust evidence regarding sediment provenance and magmatic history.

Third, detailed mineralogical investigations were not undertaken. Petrographic microscopy, X-ray diffraction (XRD), and scanning electron microscopy (SEM) analyses would improve the characterization of mineral assemblages, weathering products, and ore-related minerals.

Finally, structural geological investigations were beyond the scope of this study. Future work integrating structural mapping, fault analysis, and hydrothermal alteration studies would contribute to a better understanding of tectonic controls on magmatism, sedimentation, and mineralization within the eastern Congo Basin.

Conclusion

This study provides new insights into the geochemical characteristics of sandstones and associated magmatic intrusions from the Ubundu region in the eastern sector of the Congo Basin. The integration of major and trace element geochemistry, weathering indices, provenance discrimination diagrams, and multivariate statistical analyses allowed a comprehensive reconstruction of the geological processes that controlled sediment generation, transport, deposition, and subsequent magmatic activity.

The geochemical signatures of the sandstones indicate that the detrital material was derived predominantly from felsic to intermediate continental sources, mainly granitic and granodioritic rocks. The Chemical Index of Alteration (CIA) values reveal moderate to intense chemical weathering of the source rocks, reflecting prolonged alteration under humid tropical climatic conditions. These observations are consistent with the weathering patterns commonly reported for mature continental sedimentary systems developed on Precambrian crystalline basement terrains (Nesbitt & Young, 1982; McLennan et al., 1993).

Provenance and tectonic discrimination diagrams further suggest that sediment supply originated from a combination of stable cratonic domains and tectonically active continental environments. Such evidence supports the interpretation of a long-lived intracratonic basin influenced by episodic tectonic reactivation, which contributed to sediment recycling and compositional variability within the basin fill (Roser & Korsch, 1988; Bhatia & Crook, 1986).

The petrographic and geochemical characteristics of the granites, granodiorites, and gabbros reveal the coexistence of magmatic facies produced through progressive differentiation processes. These intrusive bodies record a complex magmatic evolution and demonstrate the importance of post-sedimentary magmatism in shaping the geological architecture of the region.

Trace-element distributions highlight significant enrichments in Fe, Ag, Sb, Au, Mo, and W. The spatial association of these elements suggests the influence of hydrothermal fluids linked to magmatic activity and points to localized metallogenic enrichment. Although the concentrations observed do not by themselves demonstrate economically exploitable mineralization, they identify favourable geochemical conditions that warrant further mineral exploration and detailed metallogenic investigations.

Overall, the results contribute to a better understanding of the geological evolution of the eastern Congo Basin by linking sediment provenance, weathering processes, magmatic differentiation, and metallogenic signatures within a unified geodynamic framework. These findings provide a valuable scientific basis for future studies on basin evolution, crustal processes, and mineral resource assessment in the Democratic Republic of the Congo.

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