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Geochemistry, Textural, and Mineralogical Maturity Indices of Gulma sandstone Member, type section of Gwandu Formation, Kebbi State, Sokoto Basin, Northwestern Nigeria

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Abstract: *Understanding the sedimentological processes, compositional evolution, and depositional environment of the Gulma Sandstone is essential for reconstructing its provenance, maturity, and paleoenvironmental history. Field mapping and laboratory analyses were conducted on Gulma Sandstone exposed in the Gulma area to elucidate its lithostratigraphy, geochemistry, petrography, mineralogical maturity, and paleoenvironment of deposition. Detailed field investigations involved systematic outcrop description based on colour, grain size, sorting, angularity, sedimentary structures, fossil content, composition, and diagenetic features. Laboratory analyses included Atomic Absorption Spectrometry (AAS) for major and trace element determination, heavy mineral analysis, petrographic examination of thin sections, and sandstone classification using modal point counts of quartz, feldspar, and rock fragments. The lithostratigraphic succession comprises whitish to purplish sandstone units exhibiting well-developed Liesegang ring structures, interpreted as products of chemical precipitation of authigenic minerals under fluctuating pore-fluid concentrations. These sandstones are overlain by claystone beds and capped by ferruginized granustone facies. Geochemical results from six representative sandstone samples show* SiO_2 *contents ranging from 54.60 to 57.29 wt% and* Al_2O_3 *from 29.20 to 31.25 wt%, while concentrations of heavy metals, trace elements, and rare earth elements (REEs) are generally low.* Fe_2O_3 *values are relatively elevated (4.60–6.50 wt%), indicating significant ferromagnesian mineral contributions. CaO concentrations range from 1.60 to 1.75 wt%, suggesting marine depositional influence associated with diagenetic calcite cementation. Other major oxides exhibit inverse relationships with* SiO_2*, reflecting progressive mineral dissolution with increasing transport distance. Sandstone maturity indices show* SiO_2/Al_2O_3 *ratios between 1.75 and 1.92, indicating appreciable clay content and limited chemical maturity. Alkali contents (*Na_2O *+* K_2O *= 1.60–2.15 wt%, average 1.91 wt%) imply moderate feldspar abundance and a felsic source rock provenance. Elevated* Fe_2O_3/K_2O *ratios (5.11–6.57) indicate ferruginized and mineralogically unstable sediments. Modal Mineralogical Index (MMI) values (1.11–2.35) place the sandstones within the Q = 50–75% and (F + RF) = 25–50% fields, suggesting texturally immature sediments. However,* $Log(Fe_2O_3/K_2O)$ *versus* $Log(SiO_2/Al_2O_3)$ *discrimination plots classify the sandstones predominantly as quartz arenites with subrounded to rounded grains, reflecting textural maturity. ZTR index values ranging from 54.05 to 83.63% further indicate mineralogically submature to mature sediments.*

Keywords: *Liesegang ring structure, Ferruginized granustone, Mineralogically immature, Texturally mature, Quartz-arenite*

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10 Introduction.

Geochemical and petrographic studies of sedimentary rocks are essential tools for understanding their mineral composition, provenance, transport history, and depositional environment. Such analyses complement traditional granulometric approaches and provide insights into post-depositional processes, sediment maturity, and classification. In this context, studying the Gulma Sandstone, a member of the Gwandu Formation in the Sokoto Basin, is crucial for unraveling the geologic history of northwestern Nigeria.

Gwandu Formation is the youngest formation in the Sokoto Basin (Koghe, 1972; Obaje, 2009). The formation was described to be ambiguous in nature with varying lithofacies composition from place to place (Ola-Buraimo *et al*., 2018). The age of the Gwandu Formation was initially dated to be Eocene (Kogbe and Sowunmi, 1975), but recent studies based on palynomorphs recovery dated it Early Miocene age (Ola-Buraimo & Haidara, 2022; Ola-Buraimo *et al*., 2022; Ola-Buraimo *et al*., 2023). In terms of paleoenvironment of deposition, the formation was first discovered to contain marine megafossils (Ola-Buraimo *et al*., 2018). It was further investigated to vary in environment from continental to marine (Ola-Buraimo and Haidara, 2022; Ola-Buraimo *et al*., 2022; Ola-Buraimo *et al*., 2023).

Previous studies have reported that the Gwandu Formation exhibits considerable variability in lithofacies composition, with ages ranging from the Eocene to the Early Miocene (Kogbe & Sowunmi, 1975; Ola-Buraimo et al., 2022). Textural analyses of sandstone members within the formation indicate environmental transitions from shallow to deeper marine settings, where fine sand particles likely settled from suspension in Middle to Outer Neritic zones (Ola-Buraimo et al., 2022). Geochemical studies of the Dukku Sandstone further support a tidal marine depositional environment, characterized by herringbone cross-stratification (Ola-Buraimo & Usman, 2022). Additionally, investigations of the Kola Sandstone suggest a paradigm shift in depositional conditions, reflecting a progression from shallow to deeper marine environments (Ola-Buraimo et al., 2022). Other workers, including Ozumba et al. (2017) and Ola-Buraimo et al. (2018), have highlighted the Gwandu Sandstone as a favorable aquifer.

The Sokoto Basin, in which the Gwandu Formation is situated, has evolved through multiple geological phases. It is widely considered to have originated from rifting that separated the South American plate from the African plate during the breakup of Gondwana. This tectonic activity was followed by marine incursions from the north (Mediterranean Sea) and south (Gulf of Guinea) (Adegoke, 1972a; Ola-Buraimo et al., 2022). Sedimentation in the basin occurred in successive phases, beginning with the deposition of Cretaceous sediments on top the Basement Complex crystalline rocks (Kogbe, 1989; Oladimeji & Ola-Buraimo, 2022; Ola-Buraimo & Mohammed, 2024). The Rima Group, comprising the Taloka, Wurno, and Dukamaje Formations, broadly dated to the Maastrichtian, overlies the Gundumi and Illo Formations (Kogbe, 1989; Hamidu et al., 2024). Subsequent phases include the deposition of the Dange and possibly Kalambaina Formations during the Maastrichtian to Paleocene, followed by the Gamba Formation in the Middle Eocene (Ola-Buraimo & Muhammed, 2024; Ola-Buraimo & Mesharck, 2024; Ola-Buraimo & Mohamed, 2024). Due to differential sedimentation patterns among the Dange, Kalambaina, and Gamba Formations, the Rima Group designation has been deemed invalid (Ola-Buraimo & Mohammed, 2024). The final phase of sedimentation in the Sokoto Basin was the deposition of the Gwandu Formation during the Early Miocene, under both continental and marine settings (Ola-Buraimo & Haidara, 2022; Ola-Buraimo et al., 2022).

This study aims to investigate the geochemical, textural, and mineralogical maturity of the Gulma Sandstone in the Gwandu Formation. It seeks to elucidate sediment provenance, depositional environment, and post-depositional modifications, providing a comprehensive geologic perspective beyond previous granulometric studies. The study area is Gulma Village located within the outskirt of Gulma, Argungu Local Government Area of Kebbi State, Nigeria. The area lies between latitude 12^0 39' 20" to 12^0 39'14" N and longitude 4^0 21' 13" to 4^0 21' 4" E with elevations between 220-240 m.

Findings from this study will enhance understanding of sedimentary processes in the Sokoto Basin, provide insights into the maturity and stability of Gulma Sandstone, and inform regional aquifer studies and resource exploration. By addressing gaps in geochemical and mineralogical knowledge, this work contributes to a more complete geological characterization of the Gwandu Formation.

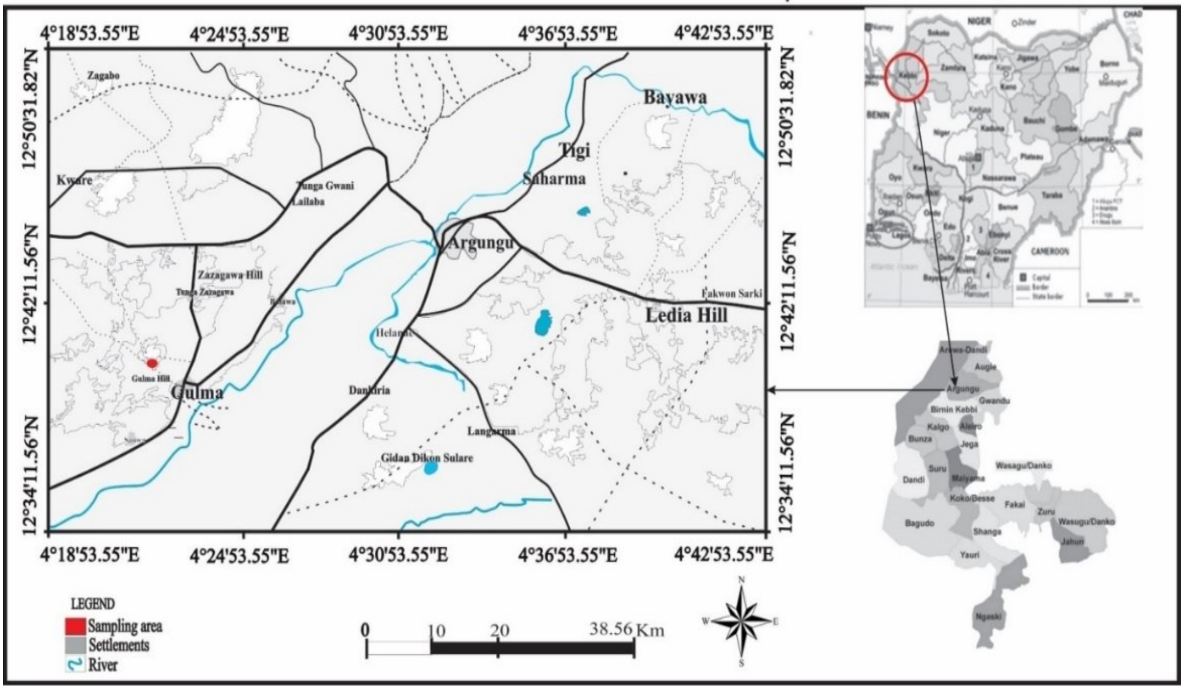

Fig. 1: Map of the study area, showing Gulma Town

2.0 Methodology

Fieldwork involved systematic ground traverses along footpaths, cattle tracks, farmlands, stream channels, and hills within the study area. Detailed field observations were made on rock types and structural features. Parameters documented include facies colour, grain size, sorting, fossil content, diagenetic features, and structural attitudes (dip and strike). Geographic coordinates of outcrops were recorded using a Global Positioning System (GPS). Representative sandstone samples were collected, properly labelled with permanent markers, and stored in sample bags for laboratory analysis.

Fresh sandstone samples were air-dried, pulverized, and prepared for geochemical and petrographic analyses. Geochemical analysis was carried out using Atomic Absorption Spectrometry (AAS), a sensitive technique for quantitative determination of major and trace metal concentrations in geological samples. Sample digestion and elemental measurements were performed following standard analytical procedures.

Petrographic analysis was conducted on selected sandstone samples using thin sections examined under a petrographic microscope to determine mineral composition, texture, and diagenetic characteristics.

Heavy mineral analysis was performed using approximately 10 g of each sample. The samples were initially washed to remove clay-sized fractions using a 63 µm British Standard (BS) sieve (Joshua & Oyebanjo, 2009; Oladimeji & Ola-Buraimo, 2022). The retained fractions were treated with 37% hydrochloric acid (HCl) for about ten minutes in a fume cupboard to remove iron coatings and carbonate cement. After acid treatment, the samples were thoroughly washed, dried, and subjected to gravity separation using bromoform with a specific gravity of 2.8 g/cm³. The separated heavy mineral fractions were rinsed, dried, and mounted on glass slides for microscopic examination under a binocular microscope.

3.0 Result and Discussion

3.1 Lithological field description

Lithological field investigation was conducted at Gulma Hill in Gulma area, Kebbi State, northwestern Nigeria. The outcrop occurs at an elevation of approximately 220 m above sea level and is located at longitude 12°39′20″E and latitude 4°21′13″N. The exposed stratigraphic succession, summarized in the lithological log presented in Figure 2, records a complex alternation of marine and continental depositional environments.

The basal unit of the section (Figure 2) consists of milky to purplish claystone that is slightly bioturbated and locally contains burrow structures. This basal claystone is overlain by a yellowish, nodular, bioturbated claystone in which nodules occur as discrete pockets. The nodules are preferentially aligned along a northwest–southeast orientation and dip southward. Sedimentary features such as load casts and burrows are well preserved within this horizon, and the contact with the underlying unit is sharp and clearly defined (Figure 2). Above this, a thickly bedded milky to purplish claystone occurs, characterized by prominent jointing, intense bioturbation, and pervasive fracturing, as illustrated in the lower to middle part of the lithological log (Figure 2).

The middle portion of the succession (Figure 2) is marked by the repetitive occurrence of yellowish nodular claystone that is moderately bioturbated relative to the lower units. This facies is overlain by reddish intercalated claystone, with a distinctly wavy and contorted contact between the two lithologies. This relationship is interpreted as reflecting a transition from a wave-influenced marine depositional setting to a more continental environment, accompanied by a progressive upward decrease in the abundance of yellowish nodules within the clay facies (Figure 2). The reddish claystone, interpreted to represent continental deposition, is subsequently overlain by purple-coloured, thinly bedded, bioturbated claystone, suggesting a return to marine depositional conditions.

Up-section, the stratigraphic succession records a clear shallowing-upward trend from relatively deeper marine deposits to shallow marginal marine conditions, as shown in Figure 2. This is expressed by the occurrence of yellowish, highly bioturbated, nodular claystone, which exhibits an undulating contact with the overlying thickly bedded reddish mudstone. The topmost unit of the succession, as depicted in Figure 2, is a highly ferruginised granustone interpreted to have been deposited in a fluviatile paleoenvironment. Gulma Hill is geomorphologically distinctive, displaying steep flanks and a broad, flat summit. A major fault was identified within the outcrop and shows a clear structural relationship with an adjoining hill, such that Gulma Hill represents the footwall block, while the adjacent hill constitutes the hanging wall.

On the opposite flank of Gulma Hill, an additional outcrop occurs at an elevation of approximately 240 m and is located at longitude 12°39′14″E and latitude 4°21′04″N. This section comprises a thickly bedded sedimentary succession beginning with a basal kaolinitic claystone facies that is strongly bioturbated and fractured and attains a thickness of about 5.8 m. This basal unit is overlain by a structurally massive reddish claystone. The uppermost unit of this section consists of a thickly bedded, variegated whitish to purplish sandstone, measuring approximately 4.5 m in thickness and displaying well-developed Liesegang ring structures. These Liesegang rings, illustrated in Plate 1A and B, represent the second documented occurrence of this feature within the Gwandu Formation. The Liesegang ring structures are interpreted to have formed under marine conditions through chemical precipitation processes associated with fluid concentration and biologically mediated slime, resulting in regularly spaced, repetitive banding patterns (Ola-Buraimo & Musa, 2024). Comparable Liesegang ring structures have been reported from the Patti Sandstone of the Patti Formation in the Bida Basin along the Lokoja–Abuja Highway (Oladimeji & Ola-Buraimo, 2022), as well as previously from the Gulma Sandstone of the Gwandu Formation (Ola-Buraimo & Musa, 2024).

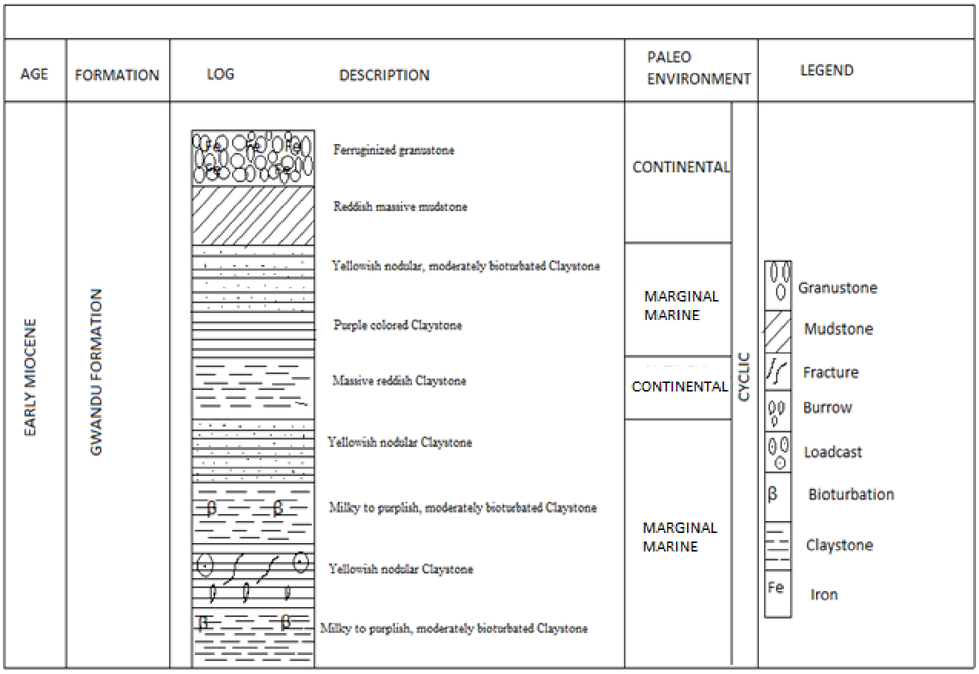

Figure 2. Litholog description of Gulma Sandstone Member

A B

Plate 1A and B. Liesegang ring structure at Gulma Hill

3.2 Geochemistry

The results of the geochemical analyses of the Gulma Sandstone samples are summarized in **Table 1**, which presents the concentrations of major oxides, selected heavy metals, and rare earth elements (REEs) for six representative sandstone samples (GS1–GS6), together with their minimum, maximum, and average values. These data provide a basis for evaluating sediment maturity, provenance, weathering intensity, and depositional environment of the sandstone facies.

Table 1. Geochemistry results of heavy metals and Rare Earth Elements (REE)

Element (wt%)	GS1	GS2	GS3	GS4	GS5	GS6	Highest value	Lowest value	Average value
SiO_2	55.93	56.495	57.29	54.6	55.58	55.45	57.29	54.6	55.89
Al_2O_3	30.2	29.45	29.75	31.2	30.2	29.2	31.25	29.2	30.0
Fe_2O_3	4.9	4.6	4.6	4.85	4.75	6.5	6.5	4.6	4.25
MnO	0.07	0.05	0.06	0.05	0.07	0.07	0.07	0.05	0.065
MgO	4.1	4.6	3.8	4.2	4.45	3.45	4.6	3.45	4.10
CaO	1.70	1.65	1.75	1.60	1.70	1.70	1.75	1.60	1.65
Na_2O	1.10	0.75	0.90	1.20	1.30	1.10	1.30	0.75	1.05
K_2O	0.85	0.90	0.70	0.80	0.85	1.00	1.00	0.70	0.85
TiO_2	1.10	1.10	1.05	1.15	1.05	1.05	1.15	1.05	1.05
P_2O_5	0.05	0.40	0.10	0.30	0.050	0.45	0.050	0.10	0.225
As	0.059	0.112	0.017	0.150	0.059	0.012	0.150	0.012	0.068
Ba	2.309	1.250	2.403	2.304	2.309	1.210	2.403	1.210	1.964
Ce	0.016	0.013	0.010	0.012	0.010	0.014	0.016	0.010	0.0125
Co	1.058	3.035	2.240	2.332	3.032	2.240	3.035	1.058	2.322
V	0.018	0.014	0.012	0.019	0.012	0.017	0.019	0.012	0.015
Cu	1.15	1.33	1.15	1.20	1.17	1.22	1.33	1.15	1.203
Cd	0.034	0.033	0.035	0.032	0.034	0.034	0.035	0.032	0.033
Nb	0.029	0.022	0.026	0.022	0.023	0.024	0.029	0.022	0.024
Ni	1.033	1.030	1.023	1.026	1.029	1.025	1.033	1.023	1.027
Pb	1.330	0.450	0.560	0.430	1.330	0.450	1.330	0.430	0.758
Sr	0.008	0.004	0.006	0.008	0.004	0.006	0.008	0.004	0.006
Rb	0.044	0.038	0.053	0.033	0.032	0.043	0.053	0.033	0.041
Y	0.088	0.085	0.050	0.063	0.058	0.080	0.088	0.050	0.071
Zr	0.013	0.015	0.012	0.013	0.015	0.010	0.015	0.010	0.013

Silicon dioxide (SiO_2) is the dominant oxide in all analysed samples, with values ranging from 54.60 to 57.29 wt% and an average of 55.89 wt% (Table 1). The relatively high SiO_2 content reflects the abundance of quartz and suggests moderate sediment maturity. Elevated silica concentrations in sandstones are commonly associated with intense physical and chemical weathering of source rocks, prolonged sediment transport, and repeated sedimentary recycling (Lindsey, 1999). In addition, silica may occur as framework quartz grains, cement, or in minor opaline phases (Lindsey, 1999). The limited variation in SiO_2 among samples likely reflects similarities in provenance and grain size, with minor variations attributable to diagenetic modification.

Aluminium oxide (Al_2O_3) concentrations range from 29.20 to 31.25 wt%, with an average value of 30.0 wt% (Table 1). These relatively high Al_2O_3 contents indicate a substantial contribution from clay minerals and feldspathic components, consistent with moderate chemical weathering of the source area. The inverse relationship commonly expected between SiO_2 and Al_2O_3 is weak in the present samples, suggesting limited compositional differentiation during transport and deposition.

Iron oxide (Fe_2O_3) values vary between 4.60 and 6.50 wt%, with an average of 4.25 wt% (Table 1). The enrichment of Fe_2O_3 reflects the influence of source rock composition and the preservation of detrital ferromagnesian and iron-bearing minerals such as amphibole, mica, ilmenite, magnetite, and their alteration products including chlorite, hematite, and clay minerals. According to Lindsey (1999), the abundance of detrital ferromagnesian minerals is controlled by their initial concentration in source rocks, hydraulic sorting during transport, and subsequent chemical alteration during weathering and diagenesis under oxidizing conditions. The relatively elevated Fe_2O_3 values observed in the Gulma Sandstone are consistent with ferruginisation noted in the field and suggest limited removal of iron during diagenesis.

Calcium oxide (CaO) concentrations range from 1.60 to 1.75 wt%, with an average of 1.65 wt% (Table 1). These values are interpreted to reflect the presence of dissolved or reprecipitated calcite cement formed during diagenesis. The occurrence of calcite cement is commonly associated with marine depositional environments, supporting field-based interpretations of marine to marginal marine conditions for parts of the Gulma Sandstone succession. Similar CaO values have been reported for marine-influenced sandstones in the Sokoto Basin and comparable sedimentary basins.

Other major oxides, including MgO, Na_2O, K_2O, MnO, TiO_2, and P_2O_5, occur in relatively low concentrations and display limited variability across samples (Table 1). Harker variation diagrams were employed to examine relationships between SiO_2 and other major oxides. The absence of systematic trends between SiO_2 and TiO_2, Fe_2O_3, CaO, Na_2O, MgO, MnO, K_2O, and Al_2O_3 suggests minimal mineral dissolution or chemical fractionation during transport and deposition. This pattern implies relatively short transport distances or rapid deposition under stable depositional conditions. However, a weak negative correlation between SiO_2 and Na_2O (Figure 3) suggests limited sodium contribution, likely derived from clay minerals rather than feldspars.

The TiO_2/Al_2O_3 ratio varies narrowly between 0.034 and 0.037, with an average value of 0.035. This ratio has been used as a proxy for grain size and sediment sorting, with lower values generally indicating finer-grained sediments. The restricted range of TiO_2/Al_2O_3 ratios observed in this study suggests uniform grain sizes and supports field and petrographic evidence of moderately to well-sorted sediments. Comparable ratios have been reported for mature to sub mature sandstones deposited in stable marine and marginal marine settings.

Trace elements and REEs, including Zr, Y, Nb, Ce, and Sr, occur in low concentrations across all samples (Table 1). The relatively low abundance of these elements suggests limited heavy mineral enrichment and supports petrographic evidence of moderate mineralogical maturity. Zircon (Zr) concentrations, in particular, show little variation, consistent with limited sediment recycling and modest contributions from highly evolved felsic source rocks. Overall, the geochemical signature of the Gulma Sandstone reflects a mixed provenance dominated by quartz-rich and clay-rich components, moderate chemical weathering, and deposition under marine to marginal marine conditions, in agreement with previous studies on the Gwandu Formation and related sandstone units in the Sokoto Basin.

3.3 *Sandstone maturity*

Sandstone maturity reflects the degree of mineralogical and textural modification experienced by sediments during weathering, transport, deposition, and diagenesis. It is commonly evaluated using grain size distribution, mineralogical composition, and the relative abundance of quartz, feldspar, rock fragments, and clay minerals. An increase in clay content is generally indicative of sediment immaturity, whereas an enrichment in quartz reflects progressive textural and mineralogical maturity (Prothero, 2004). In sandstones, clay minerals typically occur as grain coatings, pore linings, or pore-filling materials, thereby influencing porosity and permeability and, by extension, reservoir quality.

In this study, the maturity of the Gulma Sandstone was assessed using a combined geochemical and mineralogical approach. Geochemical maturity indices derived from major oxide ratios were employed alongside petrographic point-count data to provide a comprehensive evaluation of sediment maturity.

The geochemical parameters used to assess sandstone maturity are summarized in Table 2, which presents key elemental ratios commonly applied as proxies for mineralogical stability, chemical weathering intensity, and sediment recycling.

The observed SiO_2/Al_2O_3 ratio, (a widely used indicator of sediment maturity and clay content), varies from 1.75 to 1.92 with an average value of 1.86. These relatively low values suggest a high proportion of aluminosilicate phases, particularly clay minerals, indicating that the Gulma Sandstone is chemically and mineralogically immature (Potter, 1978).

Table 2. Element distribution in sandstone facies in analyzed samples

ELEMENTS	GS1	GS2	GS3	GS4	GS5	GS6	HV	LV	AV
SiO_2/Al_2O_3 Ratio	1.85	1.91	1.92	1.75	1.84	1.90	1.92	1.75	1.86
Fe_2O_3/K_2O]Ratio	5.76	5.11	6.57	6.06	5.59	6.5	6.57	5.11	5.93
Na_2O +K_2O Ratio	1.95	1.65	1.60	2.00	2.15	2.10	2.15	1.60	1.908
Mobile Oxides Al_2O_3/ ($CaO+MgO+Na_2O+K_2O$) Ratio	3.89	3.72	4.16	4.0	3.63	4.02	4.16	3.63	3.91
Determination of Calcification $CaO+MgO/Al_2O_3$	0.92	0.21	0.18	0.18	0.20	0.17	0.21	0.17	0.19
ICV for maturity $Fe_2O+Na_2O+CaO+MgO+TiO_2/$ Al_2O_{3n}	0.42	0.43	0.41	0.42	0.44	0.47	0.75	0.41	0.49
TiO_2/Al_2O_3	0.036	0.037	0.035	0.36	0.034	0.035	0.37	0.034	0.035

** HV = **Highest Value , LV = Lowest Value, AV = Average Value**

In clastic sediments, higher SiO_2/Al_2O_3 ratios are typically associated with increased quartz enrichment resulting from prolonged weathering and sediment recycling (Roser & Korsch, 1986; Roser et al., 1996). The moderate silica content observed in the analyzed samples therefore reflects limited sediment reworking and incomplete removal of less stable mineral phases.

The combined alkali content (Na_2O + K_2O), which serves as a proxy for feldspar abundance and chemical maturity, ranges from 1.60 to 2.15 with an average value of 1.91 (Table 2). These values indicate the persistence of feldspar minerals within the sandstone, further supporting a low degree of chemical maturity. Feldspars are typically susceptible to chemical weathering; their presence in appreciable amounts implies limited transport distance or relatively weak chemical alteration during sediment evolution.

The Fe_2O_3/K_2O ratio, which varies between 5.11 and 6.57 (average 5.93), is relatively high and suggests significant enrichment of iron-bearing phases relative to alkali feldspars. Elevated Fe_2O_3/K_2O ratios have been linked to post-depositional diagenetic alteration and oxidation processes in sandstones (Farquhar et al., 2014). Sandstones characterized by low SiO_2/Al_2O_3 ratios combined with high Fe_2O_3/K_2O ratios are generally mineralogically unstable and more reactive under changing geochemical conditions, such as exposure to supercritical CO_2. The Gulma Sandstone therefore falls within the category of mineralogically immature and reactive sedimentary deposits.

The observed reddish coloration of the Gulma Sandstone can be attributed to the presence of iron oxide minerals such as hematite, goethite, and limonite. These oxides are commonly enriched through weathering and oxidation processes (Muhs et al., 1987). The relatively high Fe_2O_3 content, with an average value of 4.25 wt.% (Table 1), is consistent with this interpretation and corroborates previous observations of ferruginous sandstones in similar depositional settings (Muhs et al., 1987; Ola-Buraimo and Usman, 2022).

To further evaluate the stability of mobile oxides, the Al_2O_3/(CaO + MgO + Na_2O + K_2O) ratio proposed by Gill and Yamane (1996) was applied. Values obtained range from 3.63 to 4.16 (Table 2), indicating a relatively high proportion of mobile oxides within the sandstone. This interpretation is supported by the moderate concentrations of CaO and MgO reported in Table 1. The degree of calcification, assessed using the CaO + MgO/Al_2O_3 ratio, ranges from 0.17 to 0.21 with an average of 0.19. Although these values are relatively low and insufficient to promote extensive cementation, the presence of carbonate components suggests deposition under marine or marginal marine conditions.

The Index of Compositional Variability (ICV), defined as (Fe_2O_3 + Na_2O + CaO + MgO + TiO_2)/Al_2O_3 (Cox et al., 1995), provides further insight into sediment maturity and provenance. The ICV values for the Gulma Sandstone range from 0.41 to 0.75, with an average value of 0.49 (Table 2). Cox et al. (1995) proposed that sediments with ICV values less than 1.0 are compositionally immature and typically derived from cratonic or tectonically stable source regions. Accordingly, the low ICV values obtained in this study indicate that the Gulma Sandstone is mineralogically immature and sourced predominantly from a cratonic environment.

Mineralogical maturity was further evaluated using petrographic point-count data of quartz, feldspar, and rock fragments, with results presented in Table 3. The Mineralogical Maturity Index (MMI) was calculated following the method of Nwajide and Hoque (1985). Quartz content increases progressively from GS1 to GS6, while feldspar and rock fragment contents decrease correspondingly. The calculated MMI values range from 1.11 to 2.35, with an average value of 1.60. These values fall within the maturity range defined for mineralogically immature sandstones.

Table 3. Mineral composition of sandstone facies and the mineralogical maturity index

Sample ID	Quartz (Qtz)	Feldspar (Fsp)	Rock (lithic fragment (RF)	Fsp+Rf	% Qtz	% Fsp+Rf	Mineralogical maturity index (MMI)
GS1	67	24	36	60	72.3	63.3	1.11
GS2	75	34	28	62	78	65.4	1.20
GS3	83	41	18	59	86.5	64.3	1.40
GS4	88	37	15	52	91.2	55.8	1.69
GS5	83	25	19	44	88.5	46.4	1.89
GS6	92	25	14	39	95.2	43.6	2.35
Average	81.33	31.0	21.67	52.66	85.29	56.47	1.60

Comparison of the obtained MMI values with the established sandstone maturity scale proposed by Nwajide and Hoque (1985), summarized in Table 4, shows that the Gulma Sandstone plots within the Q = 75–50% and (F + RF) = 25–50% field, corresponding to MMI values between 1.0 and 3.0. This classification confirms that the Gulma Sandstone is mineralogically immature.

Table 4. Maturity scale of sandstone (After Nwajide and Hoque, 1985)

Q =≥ 95% (F + RF) = 50%	**MI = ≥ 19 Super mature**
Q = 95-90% (F + RF) = 5-10%	MI = 19 - 9.0 Sub mature
Q = 90-75% (F + RF) = 10-25%	MI = 9.0-3.0 Sub mature
Q =75-50% (F + RF) = 25-50%	MI = 3.0-1.0 Immature
Q = < 50%	MI ≤ 1
(F + RF) > 50%	Extremely immature

Petrographic evidence supporting this interpretation is illustrated in Plates 2 and 3, which show representative point-count photomicrographs of quartz, feldspar, and rock fragments in the analyzed samples. The abundance of feldspar and lithic fragments, together with the presence of clay coatings and matrix material, is consistent with limited sediment recycling and low textural and mineralogical maturity.

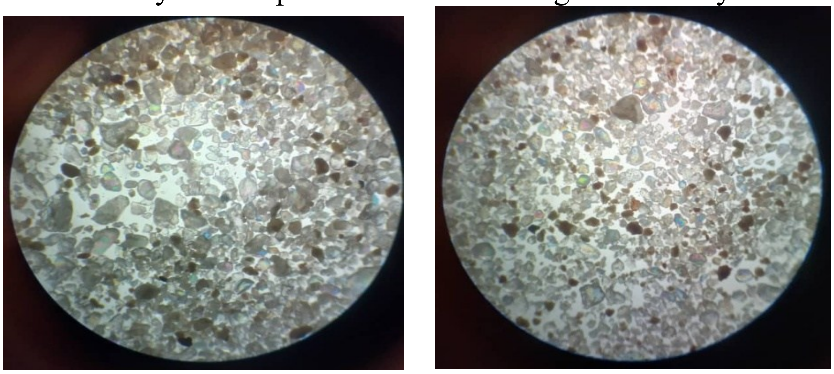

Plate 2. Point count of quartz, feldspar, and rock fragments of Samples 1 and 2

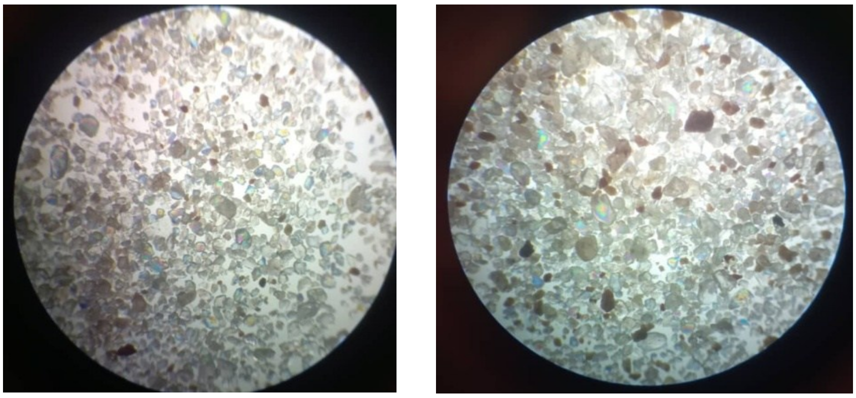

Plate 3. Point count of Quartz, Feldspar and Rock Fragments of the studied Samples 3 and 4

The integration of geochemical indices, compositional variability, and petrographic data demonstrates that the Gulma Sandstone is mineralogically immature, moderately sorted, and derived from a cratonic source under relatively limited chemical weathering and sediment reworking conditions. This maturity status has important implications for reservoir quality, reactivity, and diagenetic evolution of the formation.

Sandstone maturity is commonly evaluated using grain size distribution and mineralogical composition, where an increase in fine-grained and clay-sized particles indicates sediment immaturity. Maturity is best reflected by the relative proportions of quartz, feldspar, rock fragments, and grain-size characteristics. n increase in quartz content is generally associated with higher textural maturity, whereas clay minerals commonly occur as grain coatings, pore linings, or pore-filling material, thereby influencing porosity and permeability (Prothero, 2004) The maturity of the Gulma Sandstone was assessed using a twofold approach, incorporating mineralogical and textural maturity indices derived from geochemical and petrographic data.

The geochemical indices used to evaluate the mineralogical and chemical maturity of the Gulma Sandstone are summarised in Table 2. Clay mineral distribution plays a critical role in controlling sandstone porosity, permeability, and reservoir quality. and their characteristics as aquifer and hydrocarbon reservoirs. The SiO_2/Al_2O_3 ratios of the samples are relatively low, ranging from 1.75-1.92 (av.1.86) (Table 2).

Table 2. Geochemical maturity indices and elemental ratios of the analyzed Gulma Sandstone samples

ELEMENTS	GS1	GS2	GS3	GS4	GS5	GS6	Highest Value	Lowest Value	Average Value
SiO_2/Al_2O_3 Ratio	1.85	1.91	1.92	1.75	1.84	1.90	1.92	1.75	1.86
Fe_2O_3/K_2O Ratio	5.76	5.11	6.57	6.06	5.59	6.5	6.57	5.11	5.93
Na_2O +K_2O Ratio	1.95	1.65	1.60	2.00	2.15	2.10	2.15	1.60	1.908
Mobile Oxides Al_2O_3/ ($CaO+MgO+Na_2O+K_2O$) Ratio	3.89	3.72	4.16	4.0	3.63	4.02	4.16	3.63	3.91
Determination of Calc - ification $CaO+MgO/Al_2O_3$	0.92	0.21	0.18	0.18	0.20	0.17	0.21	0.17	0.19
ICV for maturity $Fe_2O+Na_2O+CaO+MgO+TiO_2/Al_2O_3$	0.42	0.43	0.41	0.42	0.44	0.47	0.75	0.41	0.49
TiO_2/Al_2O_3	0.036	0.037	0.035	0.036	0.034	0.035	0.037	0.034	0.035

This suggests that all the samples have high degree of clay, which indicate a chemically mineralogical immature Gulma Sandstone samples (Potter, 1978). SiO_2/Al_2O_3 ratio of clastic rock generally reflects recycling and weathering processes which can be used as an indicator of sediment maturity. Therefore, increased sediment maturity is a result of quartz particles survival preferentially to feldspars grains in a sediment suit (Roser and Korsch, 1986; Roser *et al*., 1996). However, the concentration of silica in the samples reflect moderate content, indicative of immature sediments (Tab. 2).

The alkaline content (Na_2O+K_2O) was used as a measure of the feldspar content and a measure of index of chemical maturity. In this research, the alkali content varies from 1.60 and 2.15 (av. 1.90) which is suggestive of presence of feldspar and low chemical maturity (Table 2). The Fe_2O_3/K_2O ratio ranges from 5.11 to 6.57, with an average value of 5.93, indicating enrichment in iron-bearing phases, possibly related to post-depositional diagenetic processes (Table 2). It was posited that samples with low SiO_2/Al_2O_3 ratio and a higher Fe_2O_3/K_2O ratio such as the Gulma Sandstones are mineralogically less stable and more prone to reactivity during supercritical CO_2 exposure (Farquhar *et al*.,2014).

This is the case of the Gulma Sandstone Mthatember deposit under investigation, classified as mineralogically immature sediments. The reddish coloration of the Gulma Sandstone is attributed to varying proportions of iron oxides such as hematite, goethite, and limonite. Enrichment of these oxides is mostly caused by weathering processes (Muhs *et al*., 1987). Therefore, the relatively high Fe_2O content with an average value of 4.25 (Table 1). was responsible for the slight reddish colour in the Gulma Sandstone (Muhs *et al*., 1987; Ola-Buraimo and Usman, 2022).

$Al_2O_3/(CaO+MgO+Na_2O+K_2O)$ ratio was applied to determine the stability of the mobile oxides proposed by Gill and Yamane (1996). The values vary from 4.16 to 3.63 in Table 2, and the relative quantitative values of MgO and CaO in Table 1 corroborate the facts that mobile oxides are relatively high in Gulma Sandstones. The amount of calcification in the Gulma Sandstone was based on $CaO+MgO/Al_2O_3$ molecular weight ratio which ranges from 0.17-0.21 (av. 0.19). The values obtained are low to permit sediment grains cementation, but its presence in the sandstone samples suggests deposition in marine environment (Tab. 2). However, the detrital mineralogy of the Gulma Sandsone, the Index of compositional variation (ICV), and ratio of K_2O/Al_2O_3 were applied after the work of Cox *et al.* (1995). The Index of Compositional Variation (ICV), defined as $(Fe_2O_3 + Na_2O + CaO + MgO + TiO_2)/Al_2O_3$ (Cox et al., 1995), was used to evaluate sediment compositional maturity. The ICV values range from 0.41 to 0.75, average value is 0.49, indicating mineralogically immature sediments derived from a cratonic source (Cox et al., 1995).

Cox *et al.* (1995) opined that less matured sandstone contains some clay minerals with lower ICV values that are less than 1.0, and such sandstones are described to be derived from cratonic environment. Therefore, the Gulma Sandstone characterized by less than 1.0 ICV values is indicative of mineralogically immature sediments, and derived from a cratonic environment. (Tab. 2). The Mineralogical Maturity Index (MMI) was further used to probe into the mineralogical evaluation of the Gulma Sandstone, and the result was presented in Table 3. This was achieved by petrographic point count of quartz, feldspar, and rock fragments. MMI index was calculated using the parameter proposed by Nwajide and Hoque (1985). The mineralogical maturity index was determined using the expression:

$$MMI = \frac{proportion\ of\ quartz}{Proportion\ of\ fsp + proportion\ of\ R.D} \quad (1)$$

Table 3. Mineral composition of sandstone facies and the mineralogical maturity index

Sample ID	Quartz (Qtz)	Feldspar (Fsp)	Rock (lithic fragment (RF)	Fsp+Rf	% Qtz	% Fsp+Rf	Mineralogical maturity index (MMI)
GS1	67	24	36	60	72.3	63.3	1.11
GS2	75	34	28	62	78	65.4	1.20
GS3	83	41	18	59	86.5	64.3	1.40
GS4	88	37	15	52	91.2	55.8	1.69
GS5	83	25	19	44	88.5	46.4	1.89
GS6	92	25	14	39	95.2	43.6	2.35
Average	81.33	31.0	21.67	52.66	85.29	56.47	1.60

The MMI values range from 1.11 to 2.35, with an average value of 1.60 (Table 3). This suggested that the sediments are immature (Table 3). The result obtained was integrated and compared with the Mineralogical Maturity Indices in Table 4, whereby, the result obtained belong to the Q = 75-50% (F+RF) = 25-50 % with MMI equivalent to 3.0-1.0, interpreted as mineralogically immature Gulma Sandstone.

4.5. Geochemical sandstone classification

The geochemical sandstone classification of this study was adopted after the works of Pettijohn *et al.* (1972), Blatt *et al.* (1972), Folk (1984), Herron (1988), and Lindsey (1999). The log (Fe_2O_3/K_2O) vs Log (SiO_2/Al_2O_3) plot was adopted after Heron (1988), and the calculated results were presented in Table 5.

Table 4. Maturity scale of sandstone (After Nwajide and Hoque, 1985)

Q =≥ 95% (F + RF) = 50%	**MI = ≥ 19 Super mature**
Q = 95-90% (F + RF) = 5-10%	MI = 19 - 9.0 Sub mature
Q = 90-75% (F + RF) = 10-25%	MI = 9.0-3.0 Sub mature
Q =75-50% (F + RF) = 25-50%	MI = 3.0-1.0 Immature
Q = < 50%	MI ≤ 1
(F + RF) > 50%	Extremely immature

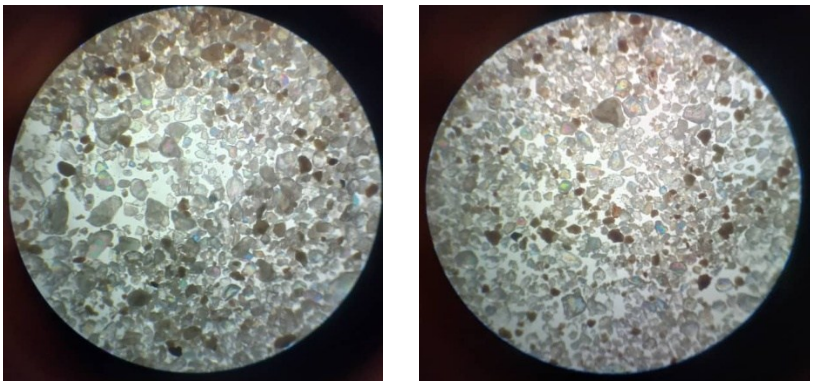

Plate 2. Point count of quartz, feldspar, and rock fragments of Samples 1 and 2

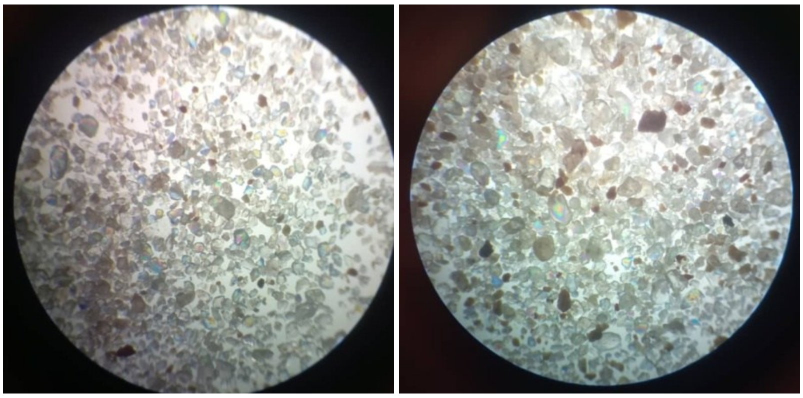

Plate 3. Point count of Quartz, Feldspar and Rock Fragments of the studied Samples 3 and 4

The value for Log Fe_2O_3/K_2O for the 6 samples ranges from 0.817-0.708 while, the value for Log SiO_2/Al_2O_3 ranges from 1.98-1.94. The samples plotted mainly in the quartz arenite sandstone classification segment (Fig. 3). This implies that the Gulma Sandstone is texturally mature but mineralogically immature. This assertion is corroborated by the roundness of the grains which vary from subrounded to rounded but dominated by rounded particles (Plts. 2 and 3).

Table 5. Chemical classification of Gulma Sandstone (After Heron, 1988)

Sample No.	Gulma 1	Gulma 2	Gulma 3	Gulma 4	Gulma 5	Gulma 6
Fe_2O_3/K_2O	5.76	5.11	6.57	6.06	5.58	6.5
Log Fe_2O_3/K_2O	0.760	0.708	0.817	0.782	0.746	0.812
SiO_2/Al_2O_3	1.85	1.91	1.92	1.75	1.84	1.90
Log SiO_2/Al_2O_3	1.96	1.98	1.98	1.94	1.96	1.96

This was carried out to corroborate the mineralogical maturity of the Gulma Sandstones. Therefore, ZTR indices were calculated by using the percentage ratio proportion of Zircon, Tourmaline and Rutile to the total number of non-opaque minerals.

4.6 Heavy Mineral Analysis

The ZTR index, defined as (Zircon + Tourmaline + Rutile) / total non-opaque heavy minerals (Hubert, 1962), was used to assess the mineralogical maturity of the heavy mineral assemblage. The calculated ZTR index for Gulma Samples 1-6 was presented in the Table 6. ZTR values for the Gulma Sandstone range from 54.05% to 83.63%, indicating sediment maturity varying from submature to mature (Table 6).

$$ZTR = \frac{Zircon + Tournaline + Rutile}{Total\ number\ of\ non\ Opaque\ minerals} \quad (2)$$

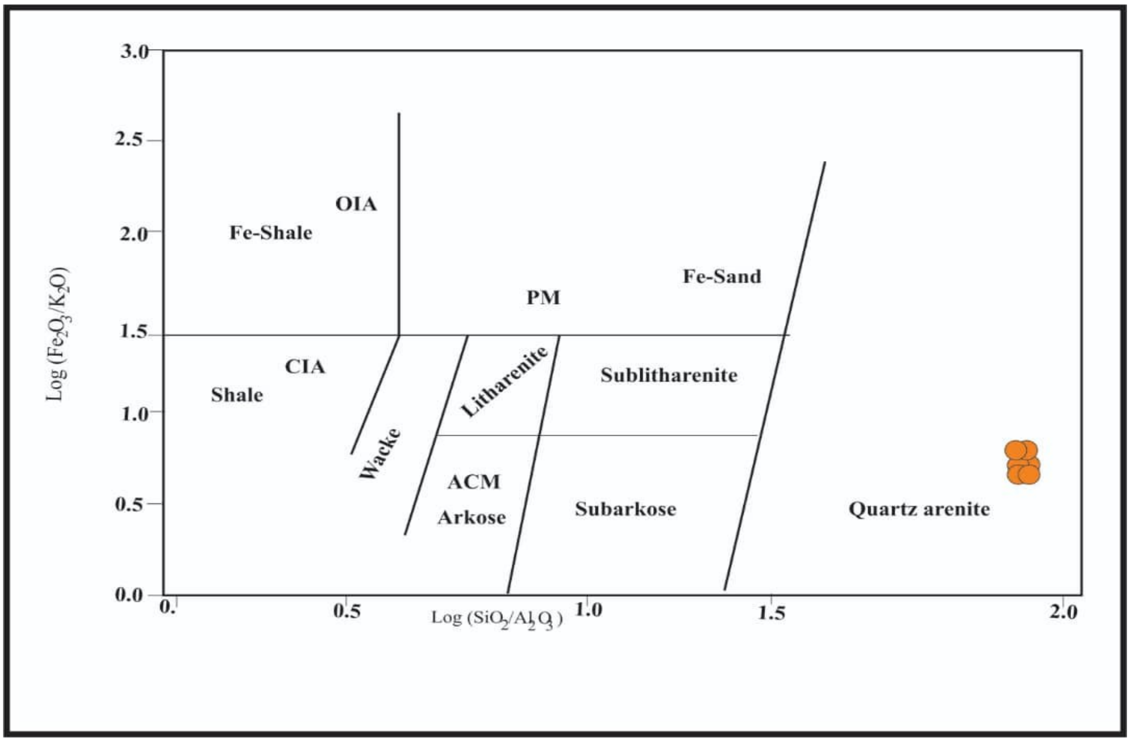

Fig. 3. Chemical classification of the Gulma Sandstone based on the log (Fe_2O_3/K_2O) versus log (SiO_2/Al_2O_3) diagram after Herron (1988)

Table 6. Heavy mineral separation counts of Gulma Sandstone

Sample No.	Zircon (Z)	Tourmaline (T)	Rutile (R)	Non-Opaque (Op)	ZTR Index %	Mineralogical maturity
Gulma 1	28	15	19	80	77.5	Mature
Gulma 2	22	13	24	89	66.29	Submature
Gulma 3	18	15	22	75	73.33	Submature
Gulma 4	22	17	20	79	74.68	Submature
Gulma 5	19	12	15	55	83.63	Very mature
Gulma 6	18	10	12	74	54.05	Submature

ZTR index is expressed in percentage and it measures the maturity of heavy mineral suite (Pettijohn *et al*., 1972). Mange & Maurer (1992) posited that the ZTR index for arkose and greywackes is between 2-39 %, and usually exceeds 90% in quartz arenites. However, ZTR index <75 % implies immature to sub mature sediments and ZTR >75 % indicates mineralogical mature sediments (Ola-Buraimo *et al*. 2022). Mange and Maurer (1992), described ZTR index values between 75 and 88 % as characteristics of mature sediments. The ZTR Index for the Gulma Sandstones is generally greater than 70 % with the exception of Samples 2 and 6. Therefore, the Gulma Sandstone is described to vary in mineralogical maturity from submature to mature sandstones (Table 6).

4.0 Conclusion

Field investigations reveal that the lithostratigraphic succession of the Gulma Sandstone Member comprises a vertically stacked assemblage of lithofacies, including whitish to purplish sandstone characterized by well-developed Liesegang ring structures with regularly repeated concentric banding. These sandstones are overlain by multiple claystone units of varying colour and bioturbation intensity and are capped by a ferruginised granustone facies, reflecting a complex interplay of marine, marginal marine, and continental depositional conditions.

Geochemical analyses of the sandstone samples indicate moderate concentrations of SiO_2 and Al_2O_3, while trace elements, heavy metals, and rare earth elements occur in generally low abundances. The relatively elevated Fe_2O_3 contents (4.6–6.5 wt%) reflect the presence of ferromagnesian minerals and secondary iron oxides, consistent with ferruginisation and post-depositional diagenetic modification. CaO values ranging from 1.60 to 1.75 wt% suggest the presence of dissolved diagenetic calcite cement, supporting a marine influence during deposition. Variations in major oxide concentrations show no systematic enrichment with increasing SiO_2, implying limited mineral dissolution with transport distance and relatively uniform sediment supply.

Sandstone maturity indices indicate contrasting textural and mineralogical characteristics. The low SiO_2/Al_2O_3 ratios (1.75–1.92) reflect appreciable clay content and point to chemical and mineralogical immaturity. Moderate alkali contents (Na_2O + K_2O) further indicate the persistence of feldspar and a felsic source rock provenance with moderate chemical weathering intensity. Elevated Fe_2O_3/K_2O ratios (5.11–6.57) suggest ferruginised sediments that are mineralogically less stable and susceptible to diagenetic alteration. Mineralogical Maturity Index (MMI) values confirm that the Gulma Sandstone is predominantly mineralogically immature.

Geochemical classification using the log(Fe_2O_3/K_2O) versus log(SiO_2/Al_2O_3) diagram places the sandstone mainly within the quartz arenite field. This classification, together with petrographic observations of subrounded to rounded grains, indicates a texturally mature sandstone despite its mineralogical immaturity. Heavy mineral analysis yields ZTR indices ranging from 54.05% to 83.63%, suggesting variable but generally moderate to high mineralogical maturity, consistent with sediment recycling and hydraulic sorting.

Overall, the integrated field, geochemical, petrographic, and heavy-mineral evidence demonstrates that the Gulma Sandstone Member represents a texturally mature but mineralogically immature sandstone deposited under mixed marine to continental conditions, derived from a felsic cratonic source and modified by post-depositional diagenetic processes.

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Ethical considerations

Not applicable

Data availability

The microcontroller source code and any other information can be obtained from the corresponding author via email.

Authors' Contribution

Ola-Buraimo Abdulrazaq Olatunji conceived and supervised the study, interpreted geochemical and petrographic data, and drafted and revised the manuscript. Sufiyanu Ahmad conducted field mapping, sample collection, laboratory analyses, and preliminary data interpretation. Both authors discussed the results, reviewed the manuscript, and approved the final version.