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Research article

Mineralogy and geochemistry of the sandstone facies of Campanian Lokoja formation in the Southern Bida basin, Nigeria: implications for provenance and weathering history

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ABSTRACT

The upper Cretaceous Lokoja Formation is the earliest deposited stratigraphic unit in the intracratonic Bida Basin, Nigeria. It consists predominantly of sandstone and offers a potential hydrocarbon reservoir in the basin. In this study, we investigated the bulk elemental (major, trace and rare earth elements) and mineralogical compositions of the sandstones for the determination of their compositional maturity, tectonic setting, source and weathering history. The sandstone geochemical data indicates that the samples contain moderate amount of SiO_2 and Al_2O_3 with average values of 78.3 % and 9.75 % respectively. Relatively high average values of K_2O (1.59 %) and Na_2O (1.52 %) and low Fe_2O_3 (2.56 %), MnO (0.05 %), TiO_2 (0.31 %) and P_2O_5 (0.018 %) were obtained. Plots of relevant geochemical elements reveal that the sandstones are predominantly arkose and litharenite types with minor sub-litharenites. Application of some trace element geochemical proxies; La/Co (11.78), Th/Co (1.32), La/Th (7.04) and Eu/Eu* (0.82) to constrain the source history suggest protolith dominated by felsic rock. Relatively low average values of ΣREEs (12.81) and ΣHREEs (1.52) support the felsic provenance of the sandstones and the tectonic setting discriminant function plots indicate passive margin depositional basin. Paleo-weathering plot reveals a moderate humid climatic condition and the mean values of CIA (79.21), CIW (90.51), PIA (66.55) and A–CN–K diagram indicates low to moderate chemical weathering in the source area and compositional immaturity for the sediments. This study concludes that the sandstones of the Lokoja Formation are immature and were derived from the faulted blocks of granitic basement rocks at the margin of the basin and deposited proximally.

1. Introduction

The northwest-southeast trending Bida Basin is located in Nigeria close to the confluence of rivers Niger and Benue. It is an intracratonic basin with rift related origin and it contains about 3.5 km thick flat lying clastic sediments (Udensi and Osazuwa, 2004). It is almost structurally perpendicular to the Anambra Basin in the southeast whereas to the northwest it is adjacent to Sokoto Basin. Sedimentation was active in these basins during Campanian-Maastrichtian time in Nigeria. The sandstones are located around the confluence of river Niger and Benue, where essentially the Lokoja Formation is exposed by road cuts along Lokoja-Abuja and Lokoja-Agbaja roads (Figure 1). The recent construction or expansion of the highway provided excellent exposures of the Lokoja Formation in the localities where it was hitherto unexposed and un-investigated.

Lokoja Formation is unique and deserves detail study as it is the earliest stratigraphic unit deposited unconformably on the Basement rocks and therefore provides a key to the geologic history and paleotectonic setting of the depositional basin. From the point of view of hydrocarbon prospectivity, being predominantly of sandstone, minor conglomerate and proximity to carbonaceous shales of the younger Patti Formation, it offers reservoir potential (Vrbka et al., 1999). Bida Basin is one the marginal basins in Nigeria being targeted for exploration and development to drive the Government target of 40 bbl oil reserve through contributions from inland basin fields. Given the scenario described above, it remains a major concern that till date, the Lokoja Formation is still poorly understood. In fact there exist conflicting opinions on the characteristics, stratigraphy (lateral and vertical extent) and paleoenvironments. Jan du Chene et al. (1978), Braide (1992) and recently Rahaman et al. (2019) lumped the entire sandstones, shales,

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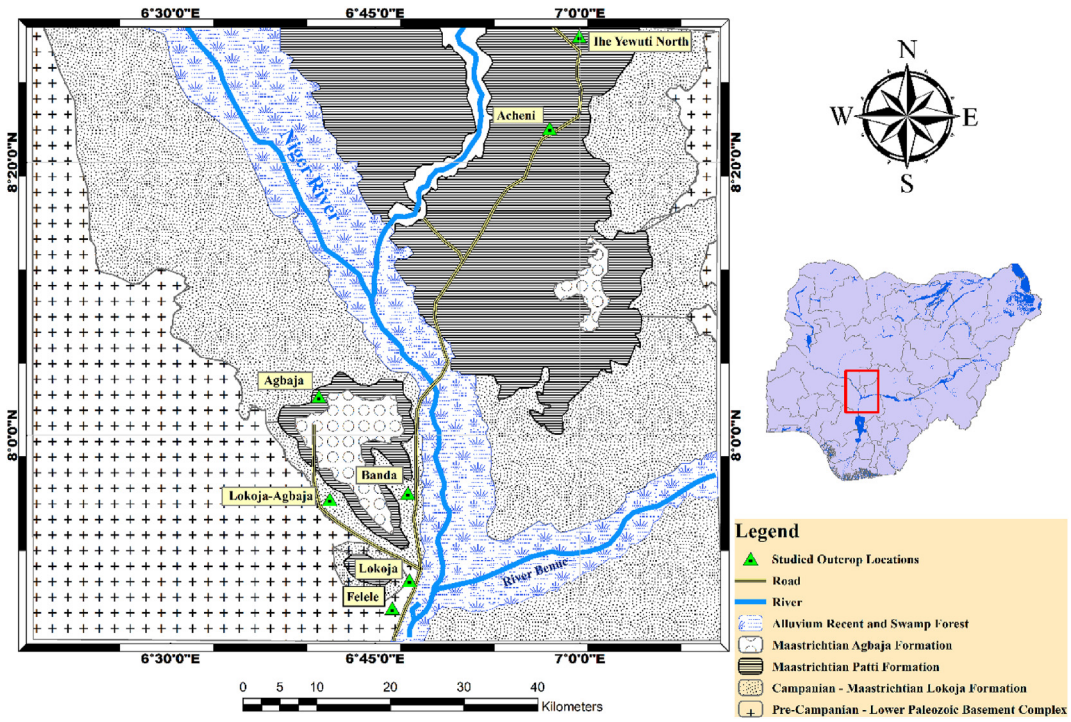


Figure 1. Map of Nigeria showing Bida Basin. Note the locations of sampled sections of Lokoja Formation.

claystones as one stratigraphic unit or formation in the Southern Bida basin called Lokoja Sandstone without regard to their source history, sedimentogical features and paleoenvironments. Ojo and Akande (2003, 2009) however, having identified and interpreted certain peculiarities of the sediments did not only uphold the earlier subdivisions (Lokoja and Patti Formations) by Jones (1958) and Adeleye (1973) but provided more evidences in support of the separation of the sandstones into different mappable packages. Ojo and Akande (2013) outlined clearly the depositional facies of the Lokoja Formation (Alluvial and braided facies) and the petrographic characteristics of the sandstone on the basis of sedimentological features and basic petrology. One of the odds against the Lokoja Formation is that it is mainly of sandstone and therefore no opportunity for fossil dating whereas the shale of the Patti Formation have been dated and even geochemically characterised (Agyingi, 1993; Ojo and Akande, 2006, 2008; Ojo et al., 2016). It is in this context that the present study is focused on elemental composition analysis of the sandstones of the Lokoja Formation in the sense of chemostratigraphy.

Geochemical tool for evaluating provenance and tectonic setting of sandstones have been well established and discussed (Bhatia, 1983; McLennan et al., 1993; Armstrong-Altrin et al., 2019; Ayala-Perez et al., 2021). In recent years, geochemistry has been increasingly applied to unravel the intrinsic nature of source rocks, tectonic setting of the emplacement of sedimentary products and levels of weathering (Armstrong-Altrin et al., 2004, 2017, 2018; Dey et al., 2009). Abundance of major, trace and rare earth elements compositions of sedimentary rocks and their ratios are useful for constraining source weathering, tectonic setting and provenance. The objective of this work is to provide an insight on the provenance of the sandstones, paleoclimate and tectonic setting of the source area.

2. Geological and regional stratigraphic setting

Quite a number of authors that have discussed the origin of the Bida Basin share the rift model origin of Bida Basin. They suggested that the evolution was linked with break of South America and Africa into separate plates (King, 1950; Kennedy, 1965; Agyingi, 1993). Interpretation of Landsat images, borehole logs as well as geophysical data across the entire Bida Basin by Kogbe et al. (1983) identified linear faults which trend northwest southeast at the margins in support of the rift origin hypothesis. The pioneer work in the Bida Basin is Falconer (1911) which described the upper Cretaceous sediments in the Bida Basin as Lokoja Series. Russ (1930) however named the sediments as Nupe Group. Jones (1958) subdivided the basin geographically into northern and southern Bida basins. The southern Bida Basin comprises of Campanian to Maastrichtian Lokoja and Patti formations with the Older Lokoja Formation overlying the Precambrian crystalline rocks unconformably. The dominant lithologic unit of the Lokoja Formation is sandstone which ranges from fine-grained to conglomeratic sandstone type (Ojo and Akande, 2003) and they are associated with minor claystone and siltstone units. The Patti Formation consisting of shale and sandstone members is succeeded by Agbaja Ironstone Formation. The lateral equivalents of the formations are preserved in the northern arm of the basin and they include the Bida Formation, Sakpe Ironstone, Enagi Siltstone, and Batati Ironstone (Figure 2).

3. Methods

The sandstone samples used for this research were collected from the exposed sections of Lokoja Formation along Lokoja-Abuja highway where recent road expansion provided excellent exposures. The sections were logged from the base to the top and continuous record of lithologic characteristics and sampling of fresh sandstone samples were also carried out. The samples were properly kept and subsequently selected for laboratory analyses such as bulk whole rock inorganic geochemical analysis and x-ray diffraction.

Selected consolidated sandstone samples were selected and thin sections were prepared by impregnating matrix-free sand with Specifix-40TM resin. The prepared thin section were basically studied for modal counting (quartz, feldspar, sedimentary lithics or rock fragments, matrix and cements with the heavy minerals). The three end members i.e. quartz, feldspar and lithics/rock fragments were re-calculated to 100 percentage to obtain framework composition in order to determine the compositional trends' change over time.

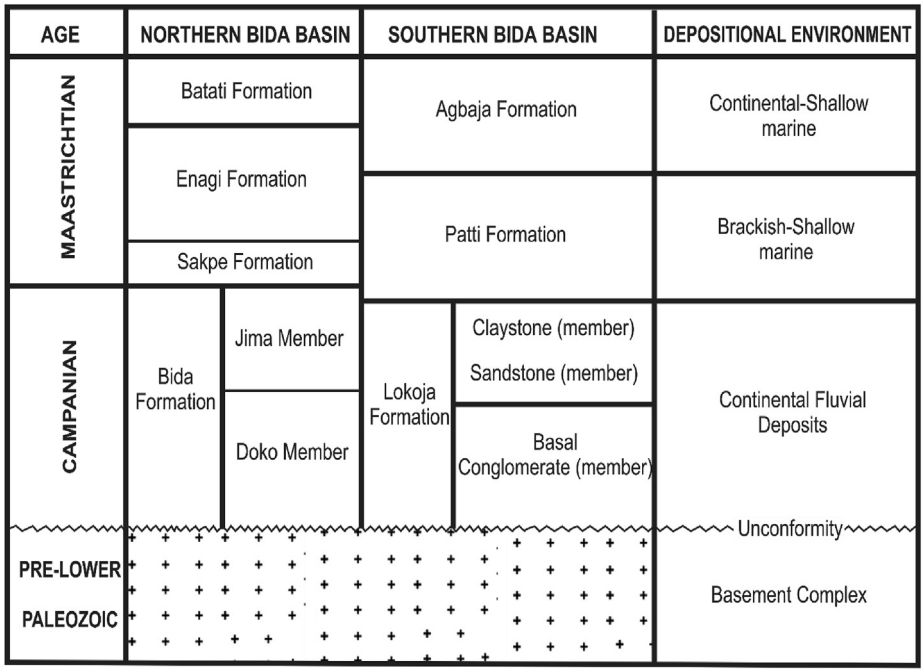


Figure 2. Generalized stratigraphic sequence of the Bida Basin.

Sixteen sandstone samples were selected for whole-rock geochemical analysis (major oxides, trace, rare earth elements) using X-Ray Fluorescence (XRF) and Inductively Coupled Plasma Mass Spectrometry (ICPMS) at the ACME Analytical Laboratories Limited, Canada. Prior to whole rock geochemical analysis, about 50–100g of each selected samples were reduced to chips of 2–4 mm and pulverized in a thoroughly cleaned agate ring mill to avoid contamination. 0.2 g aliquot of samples for the major element analysis were weighed into a graphite crucible and mixed with 1.50 g of $LiBO_2/Li_2B_4O_7$ flux and these were subjected to a temperature of 980 °C for thirty minutes. The residue was later dissolved in 5% HNO_3 (ACS grade nitric acid diluted in distilled water). Replicate analyses show that errors for major elements vary between 1 and 2%. Trace and rare elements analysis, 50.0mg of each samples was digested with mixture of 3.0 ml of concentrated HF, 1.0 ml of concentratedHNO_3 and 1.0 ml of concentrated $HClO_4$ for forty eight hours in a tightly closed Teflon vessel on a hot plate at temperature <150 °C. The solution was then dried s and extracted using 60.0 ml of 1% HNO_3. The samples were run against an internationally recognized standard reference material (SRMs) viz., GSR 4, GSR 6, GXR-6 to correct long term instrument drift. Accuracy of the trace and rare earth elements results is within 5%.

Five sandstone samples were also selected for whole rock qualitative and quantitative mineralogical composition analysis through X-ray Diffraction (XRD) at the University of Pretoria, South-Africa. For the x-ray diffraction (XRD) analysis based on the facies variations, about 50.0g of each pulverized sample were analysed used in preparation of glass discs and pressed into a steel sample holder. Glass discs were made from 0.4 g of the annealed sample powder and 4.0 g Li-tetra/metaborate while 1.0 g binder was added to 6.0 g sample material to prepare the pressed powder tablets and then analyzed with a PANalytical X'Pert Pro powder diffractometer in θ–θ configuration with an X'Celerator detector and variable divergence and fixed receiving slits with Fe filtered Co-Kα radiation (λ = 1.789Å). The diffractogram presents a permanent record of intensity against diffraction angles which is obtained directly by a strip chart recorder. The analyzed samples were scanned from 0° to 70° at a scanning speed of 0.02° 2θ/sec and the 2θ values of the peaks were converted into d-spacing in A° for Cu Kα radiations. The identified minerals within the study area as obtained by PHILLIPS PW1840 model diffractometer using nickel filtered Cu Kα radiation are presented in Table 1. The phases were identified using X'Pert Highscore plus software.

Table 1. Percentage mineralogical composition of the sandstone samples of Lokoja formation from XRD result.

Minerals	AGB1H	GER 2A	FL1B	FL2D	FL2E	FL3E
Quartz	59.56	80.95	63.57	31.16	63.13	52.03
Kaolinite	39.12	18.79	5.34	4.72	5.66	14.48
Diopside	1.32	-	3.28	-	2.62	-
Microcline	-	-	13.15	9.47	14.45	14.14
Plagioclase	-	-	13.19	7.59	14.14	19.35
Zircon	-	0.27	-		-	
Muscovite	-	-	1.46	1.83	-	
Smectite			-	45.23		

The abundance of the mineral phases (weight%) were estimated using the Rietveld method (Autoquan Program). Errors and accuracy in this analysis are on the 3 sigma level.

4. Results

4.1. Petrography and mineral composition

Petrography of Lokoja Formation sandstone listed consists mainly of quartz, feldspar, muscovite and rock fragments. It was reported that quartz grains which are mostly angular with few sub-rounded ones constitute 57–77 % of the framework composition. The polycrystalline quartz grains contain three or more individual crystals with straight and sutured inter-crystal margins. The feldspar contents consisting of plagioclase and microcline in the sandstones range between 8 to 22 % (average-16.1 %). Some of the feldspars are fresh while some have been altered along the boundary and inner part of the grains. Also, rock fragments are relatively high ranging from 1 to 10% o and made up of gneiss, phyllite and mica schist. Matrix constitutes 5–10 % of the volume of rocks and it is made up dominantly of silica and clay minerals (Ojo and Akande, 2013). The mineralogical composition of the Lokoja Formation sandstone as determined by XRD is presented in Table 1. The result reveals quartz as the dominant mineral (31.16–80.95 %). Kaolinite is present in all the samples and dominates the clay minerals (4.72–39.12

%). Other non-clay minerals include diopside, zircon, microcline, muscovite and plagioclase which occur in varying amounts.

4.2. Whole rock geochemistry

The bulk composition of sedimentary rock is largely dependent on the composition of the source rocks and the suite of sedimentary processes, in particular, source geology, weathering and diagenetic processes (Dickinson, 1985; McLennan et al., 1993; Anaya-Gregorio et al., 2018; Ramos-Vázquez and Armstrong-Altrin, 2020). The concentrations of major, trace, rare earth elements, and values of other geochemical proxies obtained from the studied sandstones are reported in Tables 2, 3, 4, and 5.

4.2.1. Major elements

The major elements composition of the Lokoja sandstones are listed in Table 2. SiO_2 (71.5–83.9 %; average - 78.3 %) and Al_2O_3 (2.10–15.23 %; average - 9.75 %) contents are moderately high. Other oxides have relatively low concentrations; Fe_2O_3 (2.56 %), K_2O (1.59 %), Na_2O (1.52 %), TiO_2 (0.31 %) and P_2O_5 (0.018 %). CaO and MgO are very low in the studied sandstones except sample GB1E which is high in CaO (10.75 %) and Na_2O contents (13.30 %).

4.2.2. Trace and rare earth elements

The trace elements distribution in the Lokoja sandstones shows varying values of some large lithophile elements Ba (39.0–1132.0 ppm), Rb (1.5–69.2 ppm) and Sr (6.90–297.0 ppm) (Table 4). Among the analyzed samples, AGB1H is noted to be markedly low in Sr, Ba and Rb and this trend correlates with exceptional low values of MgO, CaO and Na_2O content in the same sample. The average mafic trace elements Co (7.7 ppm), V (34.9 ppm) and Ni (7.5 ppm) are low in the Lokoja Formation sandstone. Th and Hf are also generally low with average of 5.8 ppm and 4.2 ppm respectively. They usually associate with heavy mineral like zircon and are therefore related to nature of the source rock. Similarly, we observed that the high field strength elements; Nb and Ta are low, having an average 5.6 ppm, and 0.5 ppm, respectively (Table 4).

Generally, the average values of REEs (12.81 ppm), light rare earth element LREEs (30.97 ppm) and heavy rare earth element-HREEs (1.52 ppm) are lower than values of Post-Archean Australian Shale-PAAS after Taylor and McLennan (1985) (184.77 ppm, 66.08 ppm and 17.61 ppm), North American Shale Composite-NASC after Gromet et al. (1984) (154.48 ppm, 134.51 ppm and 18.72 ppm) and Upper Continental Crust sediment (UCC) after Taylor and McLennan (1985) (146.37 ppm, 131.60 and 13.88 ppm). The average light rare earth elements-heavy rare earth element ratio (LREEs/HREEs; 20.88) and Europium Anomaly (Eu/Eu; 20.88 and 0.82 respectively) are however higher than PAAS (3.75 and 0.63), NASC (7.19 and 0.67) and UCC (9.48 and 0.65) (Table 6).

5. Discussion and interpretations

5.1. Sandstone classification

The geochemical classification schemes after Pettijohn et al. (1972) and Herron (1988) were applied to determine the class of the Lokoja Formation sandstones. On these plots most of the samples are plotted in arkose and litharenite fields and few are classified as sub-litharenite (Figures 3a and b).

5.2. Provenance

Typically, arkosic sands are characterized by abundant feldspars and they indicate block faulted and uplifted basement rocks from which sedimentary particles and fragments were eroded, transported and deposited proximally (Amajor, 1990; Ramos-Vázquez and Armstrong-Altrin, 2020). The predominant angular to sub-angular texture of the quartz grains in the sandstones and high amount of clayey matrix are in support of proximity to the source and compositional immaturity. This interpretation is in line with the alluvial and fluvial deposition settings ascribed to the sandstones of the Lokoja Formation (Ojo and Akande, 2013). Relationships among some major oxides and trace elements were also employed as geochemical proxies to reconstruct source-rock types and tectonic history. This is because, composition of clastic sediments in respect of major, trace and rare earth elements

Table 2. Major elements (%), CIA, CIW, ICV and PIA values of sandstone samples of the Lokoja formation.

Location	Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	TiO_2	P_2O_5	CIA	PIA	CIW	ICV
Banda	CH1A	77.9	11.27	1.47	0.97	0.19	1.85	2.34	0.02	0.43	0.02	60.56	54.35	79.99	0.65
	CH1C	83.8	8.38	1.09	0.50	0.10	1.10	2.81	0.009	0.05	0.009	59.26	43.55	83.97	0.66
	CH1D	80.2	9.05	2.31	0.37	0.20	0.38	2.03	0.009	0.10	0.009	72.14	59.34	92.35	0.60
	CH2A	73.6	12.33	2.95	1.10	0.37	1.53	1.71	0.01	0.24	0.03	65.94	63.71	82.42	0.64
	CH2C	71.5	15.23	1.88	1.33	0.30	2.17	0.75	0.01	0.31	0.01	69.13	74.33	81.31	0.44
	CH2E	82.4	8.55	1.92	0.46	0.14	0.87	2.26	0.009	0.14	0.01	64.46	51.81	86.54	0.68
Ihe/Yewuti	EJ4A	78.6	7.91	7.00	0.05	0.17	0.01	0.49	0.04	0.82	0.04	92.54	87.71	99.25	1.08
	EJ5C	72.7	9.47	7.67	0.36	0.94	0.07	1.31	0.64	1.01	0.02	81.23	72.79	95.66	1.27
	EJ6B	83.9	6.39	4.35	0.03	0.35	0.009	0.57	0.03	0.66	0.02	90.30	83.15	99.39	0.94
Felele	FL1D	74.7	13.37	1.50	0.44	0.60	0.69	2.74	0.01	0.20	0.009	73.18	61.66	92.21	0.46
	FL2E	81.0	9.93	1.06	0.76	0.30	1.42	2.25	0.009	0.08	0.009	61.74	53.48	82.00	0.59
	FL1B	81.4	9.33	0.89	0.40	0.58	0.75	2.91	0.01	0.06	0.009	64.61	47.95	89.03	0.60
Lokoja- Agbaja	AGB1E	82.5	9.03	1.99	0.03	0.12	0.07	1.51	0.01	0.19	0.01	83.35	70.68	98.90	0.43
	AGB1H	79.9	12.37	1.33	0.009	0.009	0.009	0.07	0.009	0.30	0.04	99.14	98.73	99.85	0.14
Gerinya Bridge	GB1B	76.3	11.35	3.35	0.54	0.19	0.09	1.35	0.01	0.30	0.02	81.41	75.02	94.74	0.51
	GB1E	71.9	2.10	0.26	10.75	0.18	13.3	0.27	0.009	0.13	0.03	4.79	6.93	8.03	11.86
	Mean	78.3	9.75	2.56	1.13	0.30	1.52	1.59	0.05	0.31	0.018	70.24	62.82	85.35	1.35

ICV = $(Fe_2O_3+Na_2O + CaO + MgO + TiO_2)/Al_2O_3$.
CIA = molar $[Al_2O_3/(Al_2O_3+CaO^*+Na_2O + K_2O)]\times100$.
PIA = $[(Al_2O_3–K_2O)/(Al_2O_3+CaO^*+Na_2O + K_2O)]\times100$.
CIW = $[Al_2O_3/(Al_2O_3+CaO^*+Na_2O)]\times100$.
(Nesbitt and Young, 1982), CIA = Chemical Index of Alteration, PIA = Plagioclase Index of Alteration, CIW = Chemical Index of Weathering, ICV = Index of Chemical Variability

Table 3. Ratios of some major elements of sandstone samples of Lokoja formation.

SAMPLE	CH1A	CH1C	CH1D	CH2A	CH2C	CH2E	EJ4A	EJ5C	EJ6B	FL1D	FL2E	FL1B	AGB1E	AGB1H	GB1B	GB1E	MEAN
K_2O/Na_2O	1.26	2.55	5.34	1.12	0.35	2.60	49.00	18.70	63.33	3.97	1.58	3.88	21.57	7.78	15.00	0.02	12.38
$Na_2O + K_2O$	4.19	3.91	2.41	3.24	2.92	3.13	0.50	1.38	0.58	3.43	3.67	3.66	1.58	0.08	1.44	13.57	3.11
$CaO + Na_2O$	2.82	1.60	0.75	2.63	3.50	1.33	0.06	0.43	0.04	1.13	2.18	1.15	0.10	0.02	0.63	24.05	2.65
SiO_2/Al_2O_3	6.91	10.00	8.86	5.97	4.69	9.64	9.94	7.68	13.13	5.59	8.16	8.72	9.14	6.46	6.73	34.24	9.74
Al_2O_3/SiO_2	0.14	0.10	0.11	0.18	0.21	0.10	0.10	0.13	0.08	0.18	0.12	0.11	0.11	0.15	0.15	0.03	0.13
Na_2/K_2O	0.79	0.39	0.19	0.89	2.89	0.38	0.02	0.05	0.02	0.25	0.63	0.26	0.05	0.13	0.07	49.26	3.52
Al_2O_3/TiO_2	26.21	167.6	90.5	51.38	49.13	61.07	9.65	9.38	9.68	66.85	124.13	155.5	47.53	41.23	37.83	16.15	60.24
Fe_2O/Al_2O_3	0.13	0.13	0.26	0.24	0.12	0.22	0.88	0.81	0.68	0.11	0.11	0.10	0.22	0.11	0.30	0.12	0.28
Fe_2O_3/K_2O	0.63	0.39	1.14	1.73	2.51	0.85	14.29	5.85	7.63	0.55	0.47	0.31	1.32	19.00	2.48	0.96	3.76
Fe_2O_3+MgO	1.66	1.19	2.51	3.32	2.18	2.06	7.17	8.61	4.70	2.10	1.36	1.47	2.11	1.34	3.54	0.44	2.86
Al_2O_3+K_2O + Na_2O	15.46	12.29	11.46	15.57	18.15	11.68	8.41	10.85	6.97	16.8	13.6	12.99	10.61	12.45	12.79	15.67	12.86
K_2O/Al_2O_3	0.21	0.34	0.22	0.14	0.05	0.26	0.06	0.14	0.09	0.20	0.23	0.31	0.17	0.01	0.12	0.13	0.17
$Al_2O_3/(CaO + Na_2O)$	4.00	5.24	12.07	4.69	4.35	6.43	131.83	22.02	163.85	11.83	4.56	8.11	90.30	687.22	18.02	0.09	73.41
$\{(Fe_2O_3$+MgO)/($Na_2O + K_2O$)}	0.40	0.30	1.04	1.02	0.75	0.66	14.34	6.24	8.12	0.61	0.37	0.40	1.34	16.95	2.46	0.03	3.44
log (SiO_2/Al_2O_3)	0.84	1.00	0.95	0.78	0.67	0.98	0.99	0.89	1.12	0.75	0.91	0.94	0.96	0.81	0.83	1.53	0.93
log (Fe_2O_3/K_2O)	-0.20	-0.41	0.06	0.24	0.40	-0.07	1.16	0.77	0.88	-0.26	-0.33	-0.51	0.12	1.28	0.39	-0.02	0.22
log (K_2O/Na_2O)	0.10	0.41	0.73	0.05	-0.46	0.41	1.69	1.27	1.80	0.60	0.20	0.59	1.33	0.89	1.18	-1.7	0.57
log (Na_2O/K_2O)	-0.10	-0.41	-0.72	-0.05	0.46	-0.42	-1.70	-1.30	-1.70	-0.60	-0.20	-0.59	-1.30	-0.89	-1.15	1.69	-0.56
log ({Fe_2O_3+MgO}/{$Na_2O + K_2O$})	-0.40	-0.52	0.02	0.01	-0.12	-0.18	1.16	0.80	0.91	-0.21	-0.43	-0.40	0.13	1.23	0.39	-1.52	0.05

Table 4. Trace element concentration (ppm) of sandstone samples of Lokoja formation.

Sample	Ba	Be	Co	Hf	Nb	Rb	Sr	Ta	Th	U	V	Zr	Ni	Th/U	Th/Co	Rb/Sr	Zr/Hf	La/Th	La/Co
CH1A	646.00	0.99	4.50	11.00	9.80	52.70	211.90	1.00	17.60	5.00	53.00	461.50	4.40	3.52	3.91	0.25	41.95	2.45	9.58
CH1C	664.00	0.99	3.30	1.20	2.20	62.30	145.10	0.20	1.70	0.90	7.99	50.60	4.30	1.89	0.52	0.43	42.17	4.94	2.55
CH1D	509.00	2.00	6.80	2.00	2.70	44.00	93.90	0.30	4.30	1.40	12.00	74.50	6.90	3.07	0.63	0.47	37.25	5.16	3.26
CH2A	872.00	0.99	6.30	3.00	4.40	39.10	2970	0.30	5.70	1.70	29.00	134.50	7.80	3.35	0.90	0.13	44.83	9.12	8.25
CH2C	261.00	2.00	5.40	6.60	6.70	17.80	228.60	0.60	8.30	3.20	22.00	244.20	6.20	2.59	1.54	0.08	37.00	3.49	5.37
CH2E	538.00	0.99	4.20	3.00	4.10	51.40	147.00	0.40	3.50	0.90	13.00	102.50	4.30	3.89	0.83	0.35	34.17	9.80	8.17
EJ4A	147.00	0.99	5.60	7.20	12.00	28.10	18.00	1.00	9.20	2.90	90.00	293.80	12.40	3.17	1.64	1.56	40.81	2.70	4.43
EJ5C	1132.00	1.00	59.70	7.90	13.10	69.20	20.00	1.00	8.80	2.70	120.00	324.20	33.60	3.26	0.15	3.46	41.04	3.35	0.49
EJ6B	152.00	0.99	4.60	6.80	9.10	34.00	12.60	0.70	6.90	1.80	64.00	244.00	12.90	3.83	1.50	2.70	35.88	2.35	3.52
FL1D	859.00	0.99	5.00	3.30	5.20	66.10	148.50	0.40	5.70	2.20	39.00	113.70	10.10	2.59	1.14	0.45	34.45	5.84	6.66
FL2E	693.00	0.99	3.60	1.30	2.10	48.90	187.20	0.20	1.70	1.00	16.00	55.90	3.30	1.70	0.47	0.26	43.00	8.94	4.22
FL1B	849.00	0.99	2.30	1.60	3.40	59.90	150.40	0.30	3.20	1.20	24.00	55.60	4.90	2.67	1.39	0.40	34.75	5.59	7.78
AGB1E	406.00	0.99	4.60	1.60	3.30	34.40	59.90	0.10	4.40	0.80	19.00	60.40	2.60	5.50	0.96	0.57	37.75	6.25	5.98
AGB1H	39.00	0.99	1.50	5.20	4.90	1.50	6.90	0.40	5.00	1.60	19.00	213.80	0.90	3.13	3.33	0.22	41.12	32.04	106.80
GB1B	365.00	0.99	5.20	3.10	5.30	31.60	59.90	0.40	5.90	1.00	23.00	103.60	4.60	5.90	1.13	0.53	33.42	4.88	5.54
GB1E	168.00	0.99	0.50	1.90	1.20	3.90	167.30	0.10	0.50	0.30	7.79	75.90	0.70	1.67	1.00	0.02	39.95	5.80	5.80
Mean	518.80	1.12	7.70	4.20	5.60	40.30	122.10	0.50	5.80	1.80	34.90	163.00	7.50	3.23	1.32	0.74	38.72	7.04	11.78

Table 5. Rare earth element concentration (ppm) of sandstone samples of Lokoja formation.

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	ΣLREE	ΣHREE	ΣLREE/ΣHREE	(Eu/Eu*)
CH1A	43.10	88.00	9.33	32.50	5.64	0.77	4.16	0.57	3.29	0.57	1.70	0.28	2.12	0.31	14.77	35.71	1.81	19.73	0.47
CH1C	8.40	15.20	1.92	6.50	1.16	0.46	0.92	0.13	0.60	0.13	0.44	0.05	0.41	0.06	2.79	6.64	0.38	17.47	1.32
CH1D	22.20	47.00	5.26	19.70	3.34	0.94	3.12	0.45	2.72	0.57	1.58	0.26	1.82	0.26	8.38	19.50	1.50	13.00	0.88
CH2A	52.00	79.70	6.82	24.80	3.11	0.60	1.64	0.18	1.08	0.18	0.56	0.08	0.63	0.12	13.18	33.29	0.62	53.69	0.73
CH2C	29.00	108.20	5.04	16.90	3.10	0.76	2.82	0.46	2.68	0.59	1.93	0.29	2.07	0.32	13.37	32.45	1.55	20.94	0.77
CH2E	34.30	58.00	5.17	19.30	2.46	0.55	1.97	0.23	1.20	0.25	0.65	0.10	0.60	0.09	9.60	23.85	0.71	33.59	0.74
EJ4A	24.80	45.80	5.01	16.30	3.23	0.61	3.06	0.46	3.12	0.60	1.82	0.29	1.91	0.28	8.23	19.03	1.61	11.82	0.58
EJ5C	29.50	262.30	7.48	30.20	5.89	1.12	5.40	0.82	5.30	1.20	3.41	0.52	3.89	0.53	27.46	67.07	2.93	22.89	0.60
EJ6B	16.20	30.70	3.34	12.90	2.30	0.41	2.05	0.32	1.85	0.45	1.39	0.20	1.30	0.21	5.65	13.08	1.08	12.11	0.57
FL1D	33.30	59.90	7.33	24.10	4.68	1.08	3.69	0.55	2.98	0.60	1.70	0.22	1.39	0.26	10.89	25.86	1.59	16.26	0.77
FL2E	15.20	29.10	3.02	10.60	1.75	0.49	1.60	0.24	1.06	0.29	0.70	0.10	0.63	0.10	4.98	11.93	0.66	18.08	0.88
FL1B	17.90	32.00	3.49	12.90	1.98	0.61	1.84	0.28	1.67	0.37	0.96	0.14	0.87	0.18	5.77	13.65	0.88	15.51	0.96
AGB1E	27.50	48.20	4.93	15.90	2.84	0.68	2.43	0.34	1.90	0.39	1.15	0.16	1.15	0.16	8.27	19.87	1.07	18.57	0.84
AGB1H	160.20	372.90	38.45	148.20	24.91	6.35	19.36	2.65	12.88	2.20	5.03	0.65	3.48	0.52	61.33	148.93	6.61	22.53	0.85
GB1B	28.80	52.50	5.61	19.90	2.81	0.64	2.49	0.35	2.00	0.38	1.08	0.16	0.98	0.15	9.05	21.92	1.06	20.68	0.72
GB1E	2.90	7.50	0.62	2.20	0.39	0.20	0.42	0.07	0.40	0.08	0.30	0.04	0.26	0.04	1.18	2.72	0.22	12.36	1.50
Mean	34.08	83.56	7.05	25.81	4.35	1.02	3.56	0.51	2.80	0.55	1.53	0.22	1.47	0.22	12.81	30.97	1.52	20.58	0.82

Table 6. Average chemical composition of the Lokoja formation sandstone compared with the average crust sediment values.

Elements/ Ratios	This study	PAAS (Taylor and McLennan, 1985)	NASC (Gromet et al., 1984)	UCC (Taylor and McLennan, 1985)
SiO_2	78.3	62.4	64.80	66.00
Al_2O_3	9.75	18.78	16.90	15.20
Fe_2O_3	2.56	7.18	5.66	5.00
MgO	0.30	2.19	2.86	2.20
CaO	1.13	1.29	3.63	4.20
Na_2O	1.52	1.19	1.14	3.90
K_2O	1.59	3.68	3.97	3.40
P_2O_5	0.018	0.16	0.13	-
TiO_2	0.31	0.99	0.70	0.50
SiO_2/Al_2O_3	9.74	3.32	3.83	4.34
K_2O/Na_2O	12.38	3.09	3.48	0.87
Al_2O_3/TiO_2	60.24	18.97	24.14	30.40
La/Co	11.78	1.65	1.21	3.00
La/Th	7.04	2.60	2.53	2.80
Th/Co	1.32	0.63	0.48	1.07
Th/U	3.23	4.71	4.62	3.82
Rb/Sr	0.74	0.80	0.88	0.32
Zr/Hf	38.72	42.00	31.75	32.76
REE	12.81	184.77	154.48	146.37
LREE	30.97	66.08	134.51	131.60
HREE	1.52	17.61	18.72	13.88
LREE/HREE	20.58	3.75	7.19	9.48
(Eu/Eu*)	0.82	0.63	0.67	0.65

distribution provide an insight to provenance and tectonic setting of the source area and depositional site and this has been demonstrated in several related studies (e.g. Condie et al., 2001; Joo et al., 2005; Ramos-Vázquez and Armstrong-Altrin, 2020). CaO and MgO were observed to be very low in the investigated sandstones except sample GB1E with exceptionally high CaO (10.75 %) and Na_2O (13.30 %). Petrographic studies show that the samples are rich in feldspars and the relatively high CaO and Na_2O in the GB1E could be attributed to presence of plagioclase feldspars. High iron oxide contents reported in samples EJ4A, EJ5C, EJ6B and GB1B is related to the presence iron mineral cement and subaerial weathering effects. Extremely low MgO (0.30%), MnO (0.05 %) and P_2O_5 (0.018 %) is an indication deposition under fresh water continental condition. Pearce et al. (2010) and Mücke (2000) attributed high MgO and CaO contents to influence of sea water and vice versa. Al_2O_3/TiO_2 ratio can be used for provenance reconstruction and it increases from 3 to 8 for mafic igneous rocks, 8 to 21 for intermediate rocks and 21 to 70 for felsic igneous rocks (Sugitani et al., 1996; Hayashi et al., 1997; Nagarajan et al., 2007; Armstrong-Altrin et al., 2017, 2019; Ayala-Perez et al., 2021). In this study, the calculated Al_2O_3/TiO_2 (9.65–167.60%; average-60.24%, Table 3) shows an intermediate to felsic source rocks. The average value of Al_2O_3/TiO_2 for the studied sandstone is also higher than the PAAS (18.97), NASC (24.14) and UCC (30.40) and this confirms major felsic source rock provenance (Table 6).

Ratios of trace elements such as La/Sc, Th/Sc, La/Co, Th/Co and Th/Cr and Europium anomaly (Eu/Eu*) are different in felsic and basic rocks. They are useful indicators of protolith characteristics (Taylor and McLennan, 1985; Cullers et al., 1988; Wronkiewicz and Condie, 1990; Rollinson, 1993; Cullers, 1994, 2000, 2002; Cullers and Padkovyrov, 2000; Rahman and Suzuki, 2007; Verma and Armstrong-Altrin., 2016). Comparison of the average values of La/Co, Th/Co and Eu/Eu* of the investigated sandstones with felsic and mafic rocks derived sediments and also with UCC (Table 7) show that the data substantially indicates felsic source rocks and they are lower than UCC. Cullers et al. (1988) showed that the silt fraction of sediments most closely reflects the provenance of the sediments. He further stated that feldspars and sphenes control concentrations of Ba, Na, Rb and Cs while ferromagnesian minerals influence the concentrations of Ta, Fe, Co, Sc and Cr. Therefore, average values of Ba (518.8 ppm) and Rb (40.3 ppm) and low Ta (0.5 ppm) and Co (7.70 ppm) reflect high input of felsic material. Another major remarkable observation is the high content of Sr in many of the samples (6.90–228 ppm; average-122.10 ppm) which may probably be due to high concentration of plagioclase since Sr often replace K during weathering and diagenesis.

In this study we observed very low values of Sr, Ba and Rb in sample AGB1H and this trend correlates with exceptional low values of MgO, CaO and Na_2O content in the same sample. This may be attributed to intense leaching of the unstable feldspars in the bed as it is at the transition between the sandstone of the older Lokoja Formation and younger,

Table 7. Ratios of some trace elements in Lokoja Formation sandstone and comparison with some standard values.

Elemental ratio	Present study	*Range of sediments		UCC**	PAAS***
		Felsic rocks	Mafic rocks		
La/Co	0.39–11.71	1.80–13.80	0.14–0.38	1.76	1.65
Th/Co	0.35–3.73	0.67–19.4	0.04–1.4	0.63	0.63
Eu/Eu*	0.47–1.32	0.32–0.94	0.7–1.02	0.65	0.63

Data source:
* Cullers (1994, 2000).
** Cullers and Padkovyrov (2000).
*** Taylor and McLennan (1985).

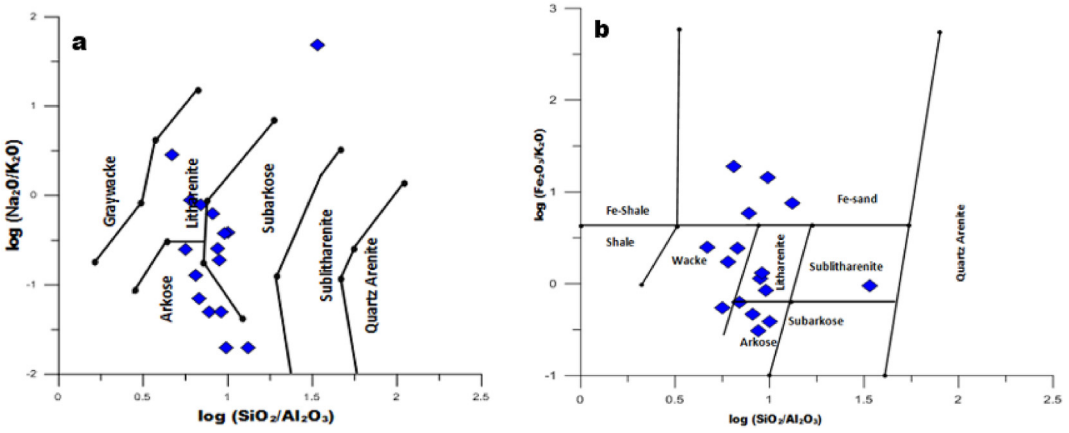


Figure 3. Bivariate chemical classification plot of the investigated sandstones of Lokoja Formation based on; (a) log (SiO_2/Al_2O_3) versus log (Na_2O/K_2O) and (b) log (SiO_2/Al_2O_3) versus log (Fe_2O_3/K_2O).

more mature Patti Formation sandstone. Sr and Ba are known to be associated with feldspathic minerals (Getaneh, 2002).

The REE pattern and Eu anomaly (Eu/Eu*) in the sedimentary rocks give insight into the nature of source rock characteristics (Taylor and McLennan, 1985; Cullers, 1994). Felsic rocks contain higher LREE/HREE ratios and negative Eu anomalies, whereas mafic rocks are characterized by LREE/HREE ratios with little or no Eu/Eu* (Cullers and Graf, 1983; Cullers, 1994). The REE patterns, therefore is useful for distinguishing between felsic and mafic source rock of clastic sediments. Cullers (1995) also concluded that felsic rocks are characterized by higher LREE/HREE ratios and negative Eu/Eu* (<1.0) whereas the mafic rocks exhibit low LREE/HREE ratio and positive but low Eu/Eu* (>1.0). The studied sandstones of Lokoja Formation have wide range of REE (2.79–61.33 ppm; average-12.81 ppm), higher light rare earth elements (LREE) (2.72–148.93 ppm; average-30.97ppm) than heavy rare earth elements (HREE) (0.22–6.61 ppm; average-1.52), high LREE/HREE ratios (20.58) and negative Eu/Eu* (0.82). REE chondrite-normalized patterns of the investigated sandstone samples of the Lokoja Formation are similar to the published data from PAAS (Taylor and McLennan, 1985), NASC (Gromet et al., 1984) and UCC (Taylor and McLennan, 1985) which is also an indication of substantial contribution from felsic provenance (Figure 4).

5.3. Tectonic setting

Geochemical indicators such as relative abundance of immobile oxides (SiO_2 and TiO_2) and depletion of the mobile phases (CaO and Na_2O) are useful (e.g., Bhatia, 1983; Roser and Korsch, 1986; McLennan et al., 1990) for discriminating tectonic settings of clastic sedimentary rocks. Major elements and their ratios (e.g. SiO_2t and K_2O/Na_2O) of clastic sediments are good indicators of paleotectonic setting (Crook, 1974; McLennan et al., 1990). Sandstones were classified into different tectonic settings based on the chemical compositions; magmatic island arcs (average SiO_2-58%, K_2O/Na_2O < 1), Andean-type continental margins (SiO_2.68 to 74%, K_2O/Na_2O < 1), Atlantic-type continental margins (average SiO_2-89%, K_2O/Na_2O > 1). Application of this parameter for the investigated sandstones shows Atlantic-type continental margins which favourably compares with continental platform sands in term of compositional characteristics. Similar to this, is the idea of Bhatia (1983) which states that sedimentary basins adjacent to oceanic island arcs typically show high abundance of Fe_2O_3+MgO (8–14%), TiO_2 (0.8–1.4%), Al_2O_3/SiO_2 (0.24–0.33) and lower K_2O/Na_2O (0.2–0.4) ratios whereas sandstones of basins adjacent to continental island arcs from oceanic island-arc types have lower Fe_2O_3+MgO (5–8%), TiO_2 (0.5–0.75) and Al_2O_3/SiO_2 (0.15–0.22) and higher K_2O/Na_2O (0.4–0.8) ratios. It was stated further that sandstones from basins on active continental margins have very low Fe_2O_3+MgO (2–5%), TiO_2 (0.25–0.45%) and K_2O/Na_2O ratio ~1 while the passive margin sandstones are generally enriched in SiO_2 and depleted in Al_2O_3, TiO_2, Na_2O, CaO with K_2O/Na_2O ratio >1. The investigated sandstones in this present study fit more into passive margin tectonic class, because they contain high average SiO_2 (78.3%) with K_2O/Na_2O ratio >1 (12.38) but relatively depleted in Fe_2O_3 (2.56 %), Al_2O_3 (9.75 %) and TiO_2 (0.31).

REEs distribution in sandstones also provides evidence of tectonic province as indicated in McLennan et al. (1990) and McLennan and Taylor (1991). They proposed that the sediments deposited in the continental margin enriched with ΣREE and LREE and negative Eu/Eu*, whereas sediments from oceanic arcs are depleted in ΣREE and LREE and lack of negative Eu/Eu*. Passive margin provenance is typically characterized by uniform REE pattern similar to PAAS, while sediments from active continental margin display intermediate ΣREE abundance with variable negative Eu/Eu* in the range of 0.6–1.0 (Bhatia, 1983; McLennan, 1989). In this study, average values of ΣREE (12.81 ppm), ΣLREE (30.97), LREE/HREE (average-20.58) and negative Eu/Eu* (0.82) obtained from the sandstones suggest a passive margin tectonic setting. Tectonic discrimination diagrams based on the bivariate plots of log (K_2O/Na_2O) versus SiO_2 (after Roser and Korsch, 1986), TiO_2 versus (Fe_2O_3+MgO), (Al_2O_3+SiO_2) versus (Fe_2O_3+MgO) and the discriminant function plot after Bhatia (1983) are very useful discrimination into broad provenance groups; Oceanic island-arc, Continental island-arc, Active continental margin and Passive margin. The tectonic discrimination plots (Roser and Korsch, 1986, 1988) for the analyzed sandstones presented in Figures 5a and b and 6a and b show clustering of most samples within Passive Margin fields (Bhatia, 1983).

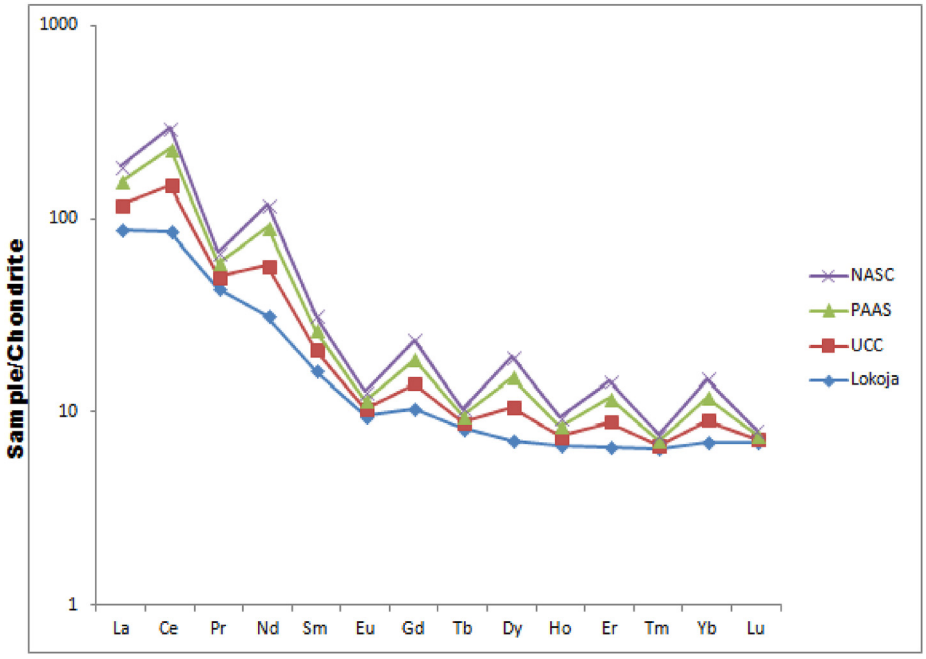


Figure 4. Chondrite normalized rare earth elements pattern of the investigated sandstones of Lokoja Formation. Note the similarity in composition and pattern with Taylor and McLennan (1985), Gromet et al. (1984) and Taylor and McLennan (1985).

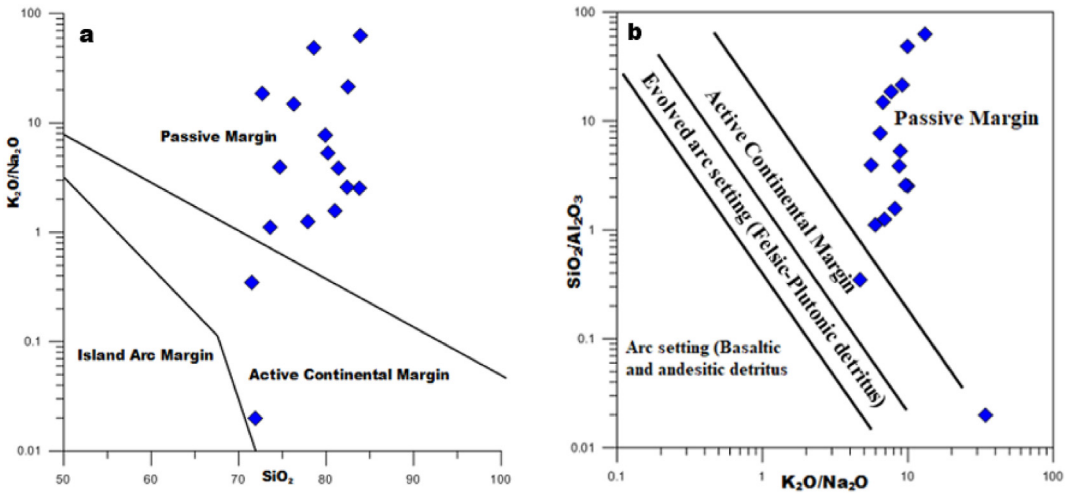


Figure 5. Bivariate paleotectonic discrimination plot of the investigated sandstones of Lokoja Formation indicating Passive Margin based on; (a) log (K_2O/Na_2O) versus SiO_2 and (b) SiO_2/Al_2O_3 versus K_2O/Na_2O.

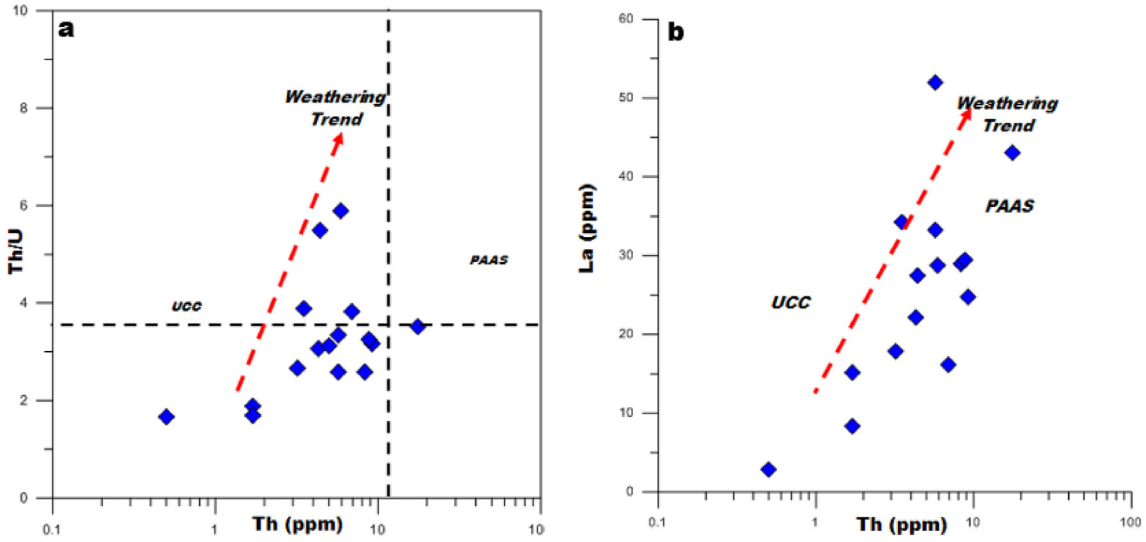


Figure 6. Bivariate provenance discrimination plot of the investigated sandstones of Lokoja Formation sorting and weathering trend based on; (a) Th/U versus Th and (b) La versus Th.

5.4. Maturity and source area weathering

The effect of weathering processes on sedimentary rocks can be measured quantitatively in terms of the relative amount of certain major oxides in the clastic sediments (Nesbitt and Young, 1982). Moderate values of SiO_2 obtained in the sandstones (71.5–83.9%; average-78.3; Table 3) indicate moderate quartz enrichment and low to moderate compositional maturity. The average SiO_2 is greater than average contents of UCC (66.00 %), NASC (64.80 %) and PAAS (62.40 %). SiO_2/Al_2O_3 ratio of sandstones has also been reported as a good indicator of sediment maturity, because, they are considered to be sensitive to sediment recycling and weathering process (Potter, 1978; Roser and Korsch, 1986). Quartz survives preferentially to feldspar, mafic minerals and lithics with increasing sediment maturity. Roser et al. (1996) further concluded that average SiO_2/Al_2O_3 ratios in unaltered igneous rocks is always $\leq$3.0 for basic rocks while for acidic rocks, it is 3.0–5.0. The values $>$ 5.0 in sandstones are however an indication of progressive maturity. The sandstones of the Lokoja Formation present average value of SiO_2/Al_2O_3 (9.74) which is greater than PAAS (3.32), NASC (3.83) and UCC (4.34) and therefore fall within sandstones of progressive maturity class (Table 6). The relatively high content of quartz in the analysed sandstones is probably due to moderate weathering under humid conditions (Table 1). Rollinson (1993) documented that alkali content ($Na_2O + K_2O$) is also an important index of chemical maturity; values less than 2 indicates little or no feldspars which signify high chemical maturity whereas values greater than 2 indicate presence of feldspar and low chemical maturity. We obtained values greater than 2 in many of the samples (average of 3.11) indicating low to moderate chemical maturity.

The rare earth elements (REEs) are moderately uniform in their concentration during weathering due to their low solubility in aqueous solutions at surface conditions (Taylor and McLennan, 1985). Gracia et al. (2004) observed that there is a preferential concentration of some relatively stable minerals (quartz and feldspar) in the coarse fraction as sorting of sediments occurred during transportation and deposition while the unstable ones are concentrated in the fine sediments. Thus, hydraulic sorting influences the chemical elemental composition of terrigenous sediments, and particularly controls the distribution of P_2O_5 and TiO_2 and trace elements like REE, Th, U, Zr, Hf and Nb). The average values of P_2O_5 and TiO_2 (0.018 % and 0.31 % respectively) in the studied sandstones closely compared with NASC (0.13 % and 0.70 %) and PAAS (0.16

% and 0.99 %) indicating poor sorting and low maturity of the sandstones. The similarity of the average values of Zr/Hf ratio (33.42–44.38 ppm; average-38.72) to the average UCC (32.76), NASC (31.75) and PAAS (42.00) lends credence to the low to moderate compositional maturity status for the Lokoja Formation sandstones. The index of compositional variability (ICV) after Cox et al. (1995) is used to evaluate samples maturity, because the increase in the degree of weathering results in enhanced alumina content but decrease in the ferromagnesian content. Higher ICV value than the PASS value ($\geq$0.85) characterizes immature sediments and mature sediments have lower value. We obtained ICV values which vary from 0.14 to 11.86 (Table 2), indicating low to moderate compositional maturity. This is consistent with the mineralogical composition of the sandstones.

McLennan et al. (1993) and Roddaz et al. (2006) suggested that Th/U ratio can be used to assess the relative contribution from mantle materials and upper continental crust since Th/U increases as weathering increases and thus kaolinite content increases. He stated further that sediments derived from the mantle materials will give Th/U ratios $<$4, whereas the ratio $\geq$4 indicates contribution from upper continental crust. Average Th/U ratio of the studied samples (3.23), though lower but similar to PAAS (4.71), NASC (4.62) and UCC (3.82) values, indicates products of chemically weathered sediments (Table 6). Average values of La/Th obtained for the studied sandstones (7.04) is higher than UCC (2.80), NASC (2.53) and PAAS (2.60) and this is indicative of significant weathering condition from the source. Weathering trends can be evaluated by using a plot of Th/U versus Th. It has been established that Th/U ratio above 4.0 is an indication of chemical weathering and/or recycling owing to more loss of U during the process (McLennan et al., 1983). The plots of Th/U versus Th according to McLennan et al. (1993) (Figure 6a) and La versus Th (Figure 6b) reveal low to moderate maturity status for the investigated samples. Rb/Sr ratio of sediments is also useful for assessing the degree of source rock weathering (Kimberley and Grandstaff, 1986; McLennan et al., 1993). This is because the chemical weathering of the source area produces higher Rb/Sr ratios in sedimentary rocks. The average Rb/Sr ratio of Lokoja Formation sandstones (0.74) is higher than the average UCC value (0.32) but closely compared to the values of the NASC (0.88) and PAAS (0.80) indicating moderate source area weathering (Table 6).

The major element geochemical composition of sedimentary rocks is dependent on chemical weathering (Nesbitt et al., 1996) and can be determined based on chemical index of alteration (CIA) and chemical index of weathering (CIW). This is obtained in molecular proportions according to Nesbitt and Young (1982, 1984, 1996). The chemical index of alteration (CIA) value indicates a higher degree of chemical alteration for the sandstones whereas chemical index of weathering (CIW) value can be due to either absence of intense recycling in a humid climate or intense recycling in an arid/semiarid climate (Osae et al., 2006). Descourvieres et al. (2011) and Fedo et al. (1995) also stated that CIA is a dimensionless parameter corresponding to increasing weathering and sediment maturity. Values ranging between 50.0 and 60.0 indicate a low degree of chemical weathering, between 60.0 and 80.0 moderate weathering while values greater than 80.0 indicate extreme chemical weathering. Generally, the increasing values of CIA/CIW from low to high is directly related to the intensity chemical weathering. Therefore, the high values of CIA (65.52–99.29; average-79.21) and CIW (81.31–99.85; average-90.51) from the study area (Table 2), reflect a moderate to an intensive chemical weathering under humid climate. Also, plagioclase index of alteration (PIA) is strongly applicable to determination of the degree of chemical weathering undergone by the rocks in the source area (McLennan et al., 1993; Fedo et al., 1995). Moderate to high PIA value for the studied sandstones (47.95–98.73; average-66.55) indicates a moderate to high weathering (recycling).

Molar proportions of Al_2O_3 (A), CaO*-Na_2O (CN), K_2O (K), FeO (F) and MgO (M) of the samples were plotted on the A–CN–K diagram (Figure 7) after Nesbitt and Young (1984) and Nesbitt et al. (1996) to deduce the chemical weathering trends. On the A–CN–K diagram, Lokoja

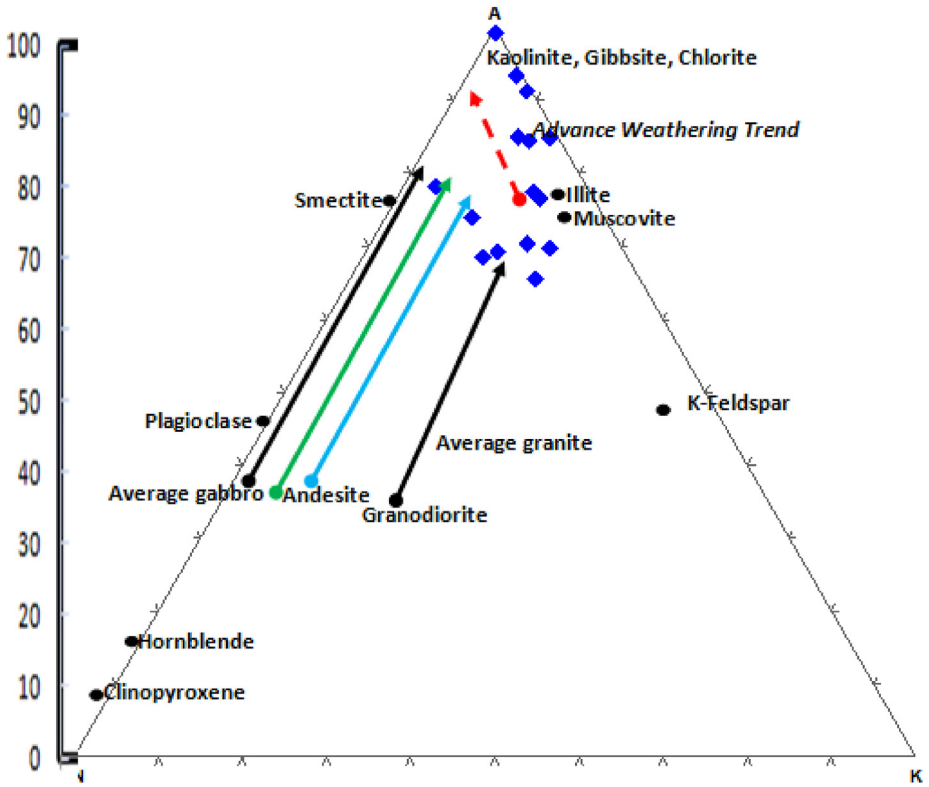


Figure 7. A–CN–K ternary plot of molecular proportions of Al_2O_3–(CaO + Na_2O)–K_2O for the investigated sandstones of Lokoja Formation showing clustering close the field of moderately to highly weathered minerals. Note the CIA on vertical scale is shown the side of the Ternary diagram and arrows 1–3 representing the weathering trends of granodiorite, adamellite and granite, respectively.

Formation sandstones plot around the "A" field, suggesting different relative contents of Al_2O_3, CaO, Na_2O and K_2O from High-K granite, gneiss and granodiorite. This position illustrates the progressive and pervasive leaching of Ca, Na and K during intensive weathering, especially from feldspars in preference to Al_2O_3 or predominance of kaolinite and/or gibbsite in the materials. This weathering trend suggests that sediments could be derived from gneiss, High-K granite and/or granodiorite. In support of the observations from A–CN–K diagram which shows the predominance of Al_2O_3, kaolinite occur in substantial amount in all the analysed samples and this therefore indicates the preponderance of aluminous clay minerals. Diopside being a mineral sourced from basic rock is a high temperature mineral and easily weathers off as sediments get transported. The occurrence of diopside in some of the sandstones points to the fact that the level of weathering or transportation is low and sediments are immature compositionally.

6. Conclusions

The investigation of the Lokoja Formation sandstones reveals arkose and litharenites as the major sandstone types. The mineralogical and compositional maturity of the sandstones is low to moderate. Geochemical weathering indices values and high proportion of certain minerals such as kaolinite, microline, diopside and muscovite lend support to the inferred low compositional maturity and short transportation history.

The Al_2O_3/TiO_2, La/Co, Th/Co and Eu/Eu* ratios of the Lokoja Formation sandstones indicate derivation from felsic rock protolith. In addition, high Al_2O_3/TiO_2, similarity of REE patterns to that of PAAS, NASC and UCC, light rare earth elements (LREE) enrichment, low heavy rare earth elements (HREE) and negative Eu/Eu* support the felsic source for the studied sandstones.

The geochemical discrimination plots and geochemical proxies reveal a passive margin for the Lokoja Formation sandstone.

Declarations

Author contribution statement

Olusola J. OJO: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Suraju A. ADEPOJU: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ayodeji AWE & Moses O. ADEOYE: Performed the experiments; Analyzed and interpreted the data.

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Data included in article/supplementary material/referenced in article.

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The authors declare no conflict of interest.

Additional information

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