Geochemical And Petrographic Studies Of Lokoja Sandstone: Implications On Source Area Weathering, Provenance, And Tectonic Setting

Madukwe, H. Y., Akinyemi, S. A., Adebayo, O. F., Ojo, A. O., Aturamu, A. O. , Afolagboye, L. O.

Abstract: Ten road - cut samples collected from five lithological sections of Lokoja sandstone formation in the Middle Niger basin were investigated using integrated granulometric, petrographic and geochemical analyses. Results of grain size analysis; standard deviation and skewness which ranges from 0.08 to -0.05 and 0.59 to -0.07 respectively suggest very well sorted to moderately well sorted sediments. Lokoja sandstone is strongly coarsely skewed and dominantly leptokurtic implying river laid sediments deposited by low energy current. The graphic mean falls between 0.1 and 1.35 suggesting mainly medium to coarse grained sediments. A mineralogical constituent includes quartz, feldspar, mica, rock fragments, clay matrix and cement fraction. The low quantities of quartz and feldspar classify the sandstone as Lithic Arenite. Heavy mineral petrographic results show that the opaque minerals constitute about 72.99% and non-opaque mineral suites of zircon, tourmaline, rutile, staurolite, sillimanite, garnet, apatite and epidote which is indicative of igneous and metamorphic sources, perhaps from the southwest and north central Basement Complex terrains. The calculated mineral maturity index (MMI) and zircon-tourmaline-rutile ratio (ZTR) indices suggest mineralogically immature to sub-mature sediments. The plot of SiO_2 versus Al_2O_3 + K_2O + Na_2O reveals semi arid to arid conditions for the Lokoja sandstone with varied maturity. The geochemical datasets reveal mature lithic arenites including sub-greywacke and protoquartzites. The chemical index of alteration (CIA) and mineralogical index of alteration (MIA) values (79.37 and 58.74 respectively) implied that their source area underwent “intense” recycling but “moderate to high” degree of chemical weathering. The discriminant function plot shows that the plotted sandstones were predominantly derived from felsic igneous source. Besides, the lower ratios of Ni/Co, Cr/Ni, Cr/Th, Cr/Sc, Th/Sc, La/Co and Th/Co suggest felsic source rock. The K_2O/Na_2O versus SiO_2 binary tectonic diagram shows source materials in the field of oceanic island arc. The Th-Co-Zr/10 and Th-Sc-Zr/10 ternary diagrams also plotted in the field of oceanic island arc.

Index Terms: geochemistry, petrography, weathering, provenance, tectonic setting, Lokoja sandstone.

◆

1 INTRODUCTION

This paper reveals the petrography and geochemistry of outcropping sediments in parts of the Southern Middle Niger Basin (Lokoja Sub-basin) (Fig. 1) based on the sandstone samples collected from five lithological sections: (1) by the side of Okene – Lokoja road (7^0 51'11.99"N and $6^0$42' 57.64"E, 7^0 51'12.29"N and 6^0 43' 4.93"E**)** and (2) Lokoja junction ($7^0$51'11.99"N and $6^0$42'57.64"E, $7^0$51'13.91"N and $6^0$42'10.91"E, $7^0$51'16.98"N and $6^0$41'51.62"E). A number of authors have worked on Late Cretaceous formation of the southern Middle Niger Basin (otherwise known as Lokoja Sub-basin) in central Nigeria (Jan du Chene et al., 1978; Idowu and Enu, 1992; Osokpor et al., 2013). The integration of petrography and geochemistry data of sedimentary rocks can reveal the nature of source rocks, the tectonic setting of sedimentary basins, and paleoclimatic conditions (Dickinson and Suczek, 1979; Valloni and Mezzardi, 1984; Bhatia and Crook, 1986; McLennan et al., 1993; Armstrong-Altrinet al., 2004; Al-Juboury, 2007; Jafarzadeh and Hosseini-Barzi, 2008; Ikhane et al., 2011; Akintola et al., 2012). The major element discrimination diagrams of Bhatia (1983) have been usually used to classify the tectonic settings of sedimentary basins and was applied in recent study (e.g., Armstrong-Altrin et al., 2004), even though caution is required in their arbitrary use (Armstrong-Altrin and Verma, 2005).

The most essential clues for the tectonic setting of basins come from the relative depletion of the oxides like CaO and Na_2O (the most mobile elements), among others. The oxides are understood to show enrichment or depletion of quartz, K-feldspars, micas and plagioclase. The ratio of the most immobile elements to the mobile ones increases towards the passive margin to the relative tectonic stability (Armstrong-Altrin et al., 2004) and hence indicating prolonged weathering. Trace elements are almost certainly transferred quantitatively into clastic sediments during weathering and transportation, reflecting the signature of the parent materials, and hence are expected to be more useful in discerning tectonic environments and source-rock compositions than the major elements (Bhatia and Crook, 1986; McLennan, 1989; Condie, 1993). Conversely, rare earth elements (e.g., La, Ce, Nd, Gd, Yb), Y, Th, Zr, Hf, Nb, and Sc) are most suited for the discrimination of provenance and tectonic setting because of their relatively low mobility during sedimentary processes and their short residence times in seawater (Taylor and McLennan, 1985; Bhatia & Crook, 1986; Wronkiewicz & Condie, 1987, 1989 and 1990). Consequently, elemental ratios such as La/Sc, La/Co, Th/Sc and Zr/Cr have been found to be good discriminators between mafic and felsic source rocks (Tijani et al., 2010). Trace elements such as La, Th and Zr are said to be more concentrated in felsic igneous rocks while Co, Sc and Cr have higher concentrations in mafic rocks (Ronov et al., 1974; Wronkiewicz and Condie, 1987, 1990). Several studies have been carried out on the Late Cretaceous sediments of the Southern Middle Niger Basin. These studies have centered mainly on the sedimentology (Adeleye and Dessauvagie, 1972; Omali et al., 2011), biostratigraphy and biozonation (Jan du Chene et al., 1978; Oloto, 1994), paleodepositional environment (Akande et al., 2005; Agyingi, 1993; Ojo and Akande, 2006, 2008), tectonics (Kogbe et al., 1983; Ojo and Ajakaiye, 1976, 1989), hydrocarbon generation potential (Idowu & Enu, 1992, Obaje et al., 2011), paleodepositional

---

- *Madukwe, H. Y., Akinyemi, S. A., Adebayo, O. F., Ojo, A. O., Aturamu, A. O. , Afolagboye, L. O.*
- *Department of Geology, Ekiti State University Ado-Ekiti, Nigeria. P.M. B. 5363, Ado Ekiti.*
- *Corresponding author: akinyemi70@gmail.com*

environment and sequence stratigraphy (Osokpor et al., 2013). This present study focused on petrography and evaluation of major and trace element geochemistry of the Lokoja Formation, southern middle Niger basin. This will consecutively reveal mineralogy, elemental distribution pattern, inferring their provenance, tectonic settings, weathering signatures and paleo-redox condition.

2. Geological setting of Middle Niger basin

The Middle Niger (Bida) Basin is a linear intracratonic sedimentary basin situated in central Nigeria. It trends NW – SE and roughly perpendicular to the Benue Trough. It is separated from the basal continental bed of the Sokoto Basin by a narrow outcrop of the crystalline basement rocks in the west and it is adjacent to the Anambra Basin in the east (Fig.1). The basin occupies a gently down warped trough (Osokpor and Okiti, 2013). The epeirogenesis responsible for the basin genesis appears closely connected with the Santonian tectonic crustal movements which mainly affected the Benue Basin and SE Nigeria. The underlain basement complex perhaps has a high relief (Jones, 1955) and the thick sedimentary successions is approximately 2000 metres as shown by gravity survey (Ojo and Ajakaiye, 1976), comprised of unfolded post-tectonic molasse facies and thin marine strata. Borehole logs, Landsat images interpretation, and Geophysical data across the basin suggest that it is bounded by a NW-SE trending system of linear faults (Kogbe et al., 1983). Gravity survey studies also corroborate central positive anomalies flanked by negative anomalies (Ojo, 1984; Ojo and Ajakaiye, 1989). This trend show agreement with rift structures as observed in the adjacent Benue Trough/Basin. A detailed study of the facies indicates rapid basin-wide changes from various alluvial fan facies through flood-basin and deltaic facies to lacustrine facies (Braide, 1992b). Accordingly, a simple sag and rift origin earlier suggested (King, 1950; Kennedy, 1965; Kogbe et al., 1981; Whiteman 1982; Braide, 1992b; Ojo and Ajakaiye, 1989) may not account for the basin's evolution (Osokpor and Okiti, 2013). Braide (1992a) paleogeographic reconstruction suggests lacustrine environments were widespread and elongate.

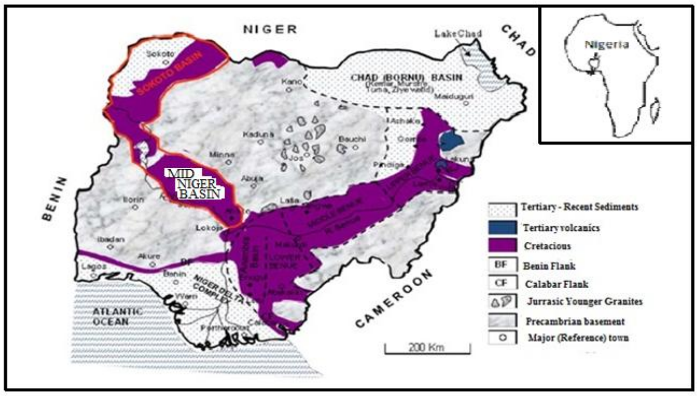

Figure 1.*Geological map of Nigeria showing locations of Middle Niger Basin (After Obaje et al., 2004).*

Lacustrine environments occurred at the basin's axis and close to the margins. This suggests that the depocenter must have migrated during the basin's depositional history and subsided rapidly to accommodate the 3.5 km thick sedimentary fill (Osokpor and Okiti, 2013). The sedimentary sequences are Late Cretaceous (Campanian – Maastrichtian) in age and were named the Nupe Sandstone by Russ (1930). Adeleye (1972) subdivided Nupe sandstone (Group) into four formations: Bida Sandstone (oldest), Sakpe Ironstone, Enagi Siltstone and Batati Ironstone (youngest). A lateral facies variation occurs in the basin. Around Lokoja, the sequence is usually referred to as the Lokoja Sandstone. Nonetheless, the Sandstone is only partly equivalent to the Nupe Sandstone (Dessauvagie, 1975) and is overlain by Patti Formation (Jones, 1955). The Bida area and Lokoja area are considered as stratigraphically different. The Lokoja, Patti and Agbaja formations occur as the three formational units in the southern Middle Niger basin (Osokpor and Okiti, 2013). The Lokoja Formation consists of pebbly clayey grit and sandstone, coarse-grained cross bedded sandstone, and few thin oolitic iron stones. A basal conglomerate of well-rounded quartz pebbles in a matrix of white clay is rarely exposed. Its thickness depends on the relief of the underlying Basement Complex floor and varies between 100 and 300 metres (Dessauvagie, 1975). The Patti Formation is a sequence of fine to medium-grained, grey and white sandstones, carbonaceous siltstone, clay stone, shale and oolitic ironstone. Thin coal seams may be present and white gritty clays are common. The maximum exposed thickness is 70 m (Jones, 1955), while the oolitic ironstones range from 7-16 m thick. The strata yielded a few non-diagnostic plant remains (Dessauvagie, 1975). A Maastrichtian (and possibly Senonian) age was thus assigned to it based mainly on correlation with other formations e.g. the Nupe Sandstone and Enugu Shale of Campano-Maastrichtian age (Jan Du Chene et al., 1979) having recorded a palynomorph assemblage and a foraminifera fauna respectively from the Lokoja area. The micro fauna in the formation is considered to be of a marsh assemblage. The palynomorphs are made up mainly of pollen and spores, the assemblage of which is indicative of a Maastrichtian age (Jan Du Chene et al., 1979). Dessauvagie (1975) shows that Patti Formation yielded fossil plants (from the carbonaceous beds) and dates the formation as Campanian to Maastrichtian.

3. Materials and methods

The methods of investigation involved both field study and laboratory analyses. Bedding characteristics in term of texture and lithology were studied in the field. Laboratory investigations of samples included grain size analysis, petrography and geochemical analysis. Ten sandstone samples were collected from Lokoja and environs: 2 samples each from 5 locations (Fig. 2). Each sample was divided into 3 parts: One part for grain size analysis, another for heavy minerals and petrographic studies and the third part for geochemical analysis.

3.1 Granulometric analysis

The grain size distributions were mechanically determined in Sedimentology Laboratory of the Geology and Applied Geophysics Department, Federal University of Technology, Akure, using Durham GeoSlope shaker mounted with a set of sieve, 100 g of each sample was agitated for 20 minutes. British Standards were employed with a sieve set in the order of mesh sizes: 2.00, 1.18, 0.85, 0.60, 0.425, 0.30, 0.0025, 0.50, 0.10, 0.075 and 0.0063 mm (Table 1). The fraction of each mesh size was weighed for statistical analysis based on the procedure of Folks and Ward (1957).

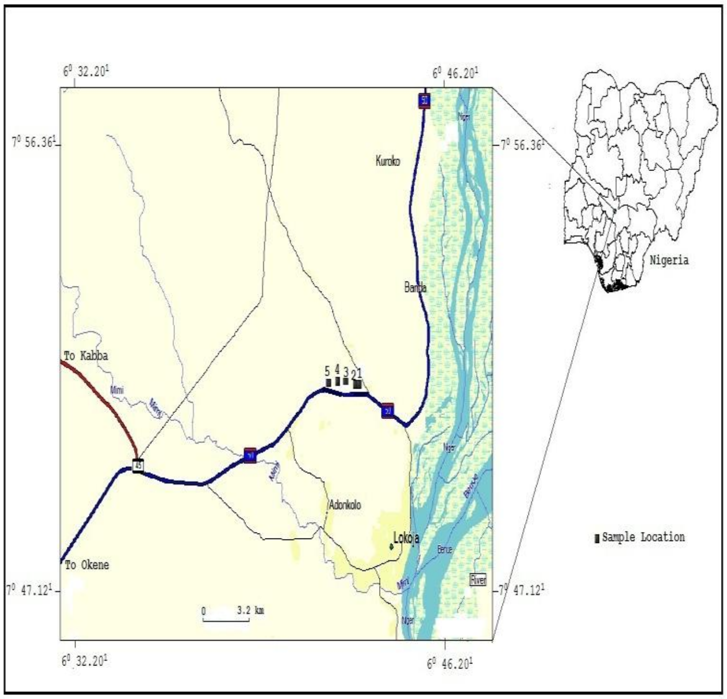

Figure 2: *Map of the study area showing sample locations*

3.2 Petrographic analysis

Each sample was made into solution with water in glass cylinders, properly agitated and left for 10 minutes to aid disaggregation. The samples were subsequently soaked with 30% hydrogen peroxide (H_2O_2) solution for total deflocculation. Consequently, the heavy minerals were separated by panning and mounted on glass slide for petrological observation under the microscope.

3.3 Geochemical analysis

The bulk chemical compositions of the sandstone samples were determined with X-ray fluorescence (XRF) spectrometry. Each samples were oven-dried at 100 ºC for 12 h to remove the adsorbed water and then crushed with a mortal and pestle to a fine powder. A PW1480 X-ray fluorescence spectrometer using a Rhodium tube as the X-ray source was used. The technique reports concentration as % oxides for major elements and ppm for minor elements.

4. Results and discussion

4.1 Grain size distribution

Table 1 shows the passing percentage values for the respective sieve diameter while Fig. 3 shows plot of particle size distribution of samples from the locations. Bivariate scatter plots based on Friedman (1969), and Folk and Ward (1957) depicts that the Lokoja sandstone are of river sand and fluvial deposited by low energy currents (Fig. 4) which agreed with previous work by Omali et al. (2011).

Table 1: Grain size analysis for Lokoja sandstone

	Percentage Passing									
Sieve Size (mm)	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
1.8	64.56	57.21	90.24	89.6	64.63	67.31	70.25	61.09	91.37	91.74
1	44.28	41.78	85.41	85.73	50.5	64.18	57.39	48.59	87.16	88.12
0.85	27.81	28.25	80.48	82.98	44.49	61.35	52.96	36.29	83.05	85.1
0.6	20.18	20.99	75.35	78.29	38.68	56.41	50.15	32.36	78.74	80.46
0.425	14.26	15.14	60.46	72.78	32.06	51.26	46.43	28.83	73.12	75.23
0.3	9.44	8.88	27.97	37.72	27.05	27.04	30.25	20.97	46.14	36.56
0.212	5.82	4.64	8.65	18.76	21.84	18.06	19.6	12.7	26.48	16.52
0.15	3.01	2.12	4.53	12.23	16.43	11.2	10.75	8.27	11.13	11.08
0.106	1.61	0.71	2.21	6.93	9.82	6.86	5.33	4.64	6.22	6.45
0.075	0.3	0.2	1.21	3.26	4.81	3.63	3.12	2.02	2.81	3.02

4.2 Petrography and geochemistry

Table 2 shows the mineralogical composition of Lokoja sandstone. Mineralogically, the Lokoja sandstone consists on the average 55.0 % Quartz, 14.0 % Feldspar, 4.0 % Mica, and 14.2 % Rock Fragment and 10.4 % clay matrix and cement fraction. The low quantities of quartz and feldspar classify the sandstone as lithic arenite (Table 2). The mineral maturity index is calculated using the mineralogical maturity index proposed by Nwajide and Hoque (1985) (Table 2),

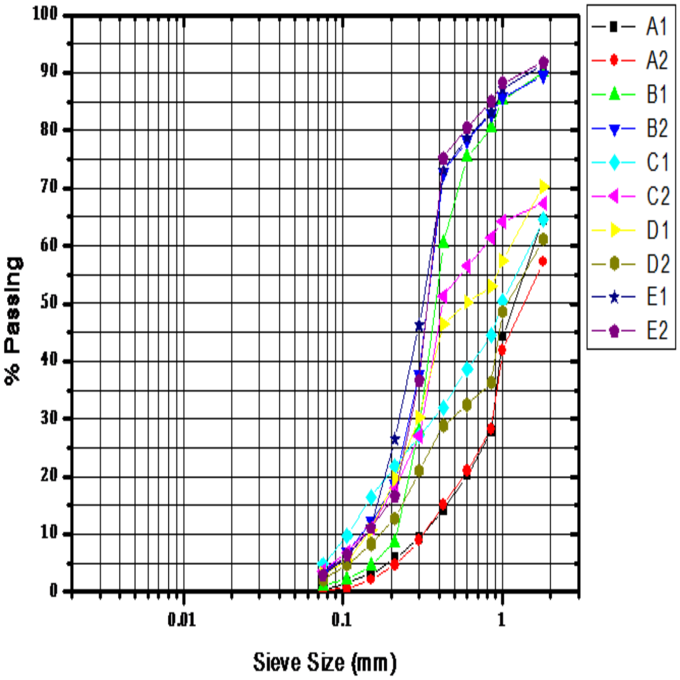

Figure 3: *Plots of particle size distribution curve for Lokoja sandstone*

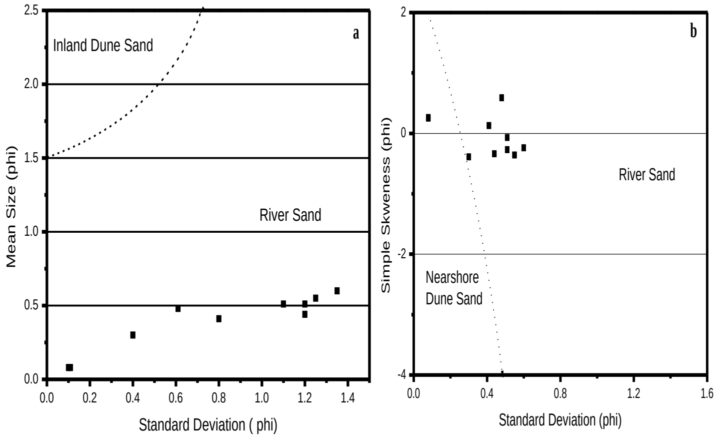

Figure 4: *Depo-environmental discrimination of Lokoja sandstone: (a) Based on Friedman (1969) and (b) Based on Folk and Ward (1957).*

Table 2: Mineralogical composition of Lokoja sandstones from thin section study

Sample no	Quartz	Feldspar	Mica	Rock fragment	Matrix and cement	MMI
1A	52	20	3	8	13	1.86
1B	45	15	5	20	15	1.29
1C	58	8	4	18	10	2.23
1D	60	12	3	15	7	2.22
1E	60	15	5	10	7	2.40
Average	55	14	4	14.2	10.4	2.00

MMI = Mineralogical maturity index.

the mineralogical maturity index is calculated thus;

$$MMI = \frac{\text{Proportion of Qtz}}{\text{Proportion of Fsp} + \text{Proportion of R. F}}$$

Since MMI value is less than 3.0 but greater than 1.0 as calculated above; hence the studied samples are said to be mineralogically immature sediments (Nwajide and Hoque, 1985; Igwe et al., 2013) (Table 3).

Table 3: Maturity scale of Sandstone: Limiting % of Q and (F + RF) MI and maturity stage (Nwajide and Hoque, 1985; Igwe et al., 2013).

Q =≥ 95% (F + RF) = 50%	MI = ≥ 19 supper 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 =75-5O% (F + RF) = 25-50%	MI =3.0-1.O immature
Q = < 50%	MI ≤ 1
(F + RF) > 50%	Extremely immature

Heavy mineral petrographic results show opaque mineral constitute about 72.99% mainly of haematite, ilmenite, magnetite and pyrite (Omali et al., 2011) and non-opaque mineral suite of zircon, tourmaline, rutile, staurolite, sillimanite, garnet, apatite and epidote (Table 4) suggestive of igneous and metamorphic sources, probably from the southwest and north central Basement Complex terrains (Omali et al., 2011). The high percentage of hematite reflects oxidizing environment. The calculated average ZTR% index of 53.97 % with apatite as the least abundant of ultra-stable minerals indicates sub-mature to mature mineralogy of the sandstone. These heavy mineral suites occur as basement complex of igneous and metamorphic rocks sediments derivatives (Gideon et al., 2014).

Table 4: Composition of heavy mineral suites for Lokoja sandstones

Sample	Zircon	Tourmaline	Rutile	Staurolite	Sillimanite	Garnet	Apatite	Epidote	Non-opaque	ZTR index (%)	Opaque
2A	6	4	12	12	2	1	-	1	38	57.89	88
2B	4	3	7	11	1	2	-	2	30	46.67	76
2C	6	4	7	10	1	1	1	1	31	54.84	93
2D	7	4	5	10	1	2	1	1	31	51.61	114
2E	5	6	9	9	1	2	1	2	34	58.82	72
Total	28	21	40	52	6	8	3	7	164	269.83	443
Percent	17.07	4.74	24.39	19.27	3.66	4.88	1.83	4.27			72.99

The “ZTR” index which is a quantitative definition of mineral assemblage was calculated using the percentage of the combined zircon, tourmaline and rutile grains for each sample (Hubert, 1962; Ikhane et al., 2013) according to the formula below.

$$\text{ZTR index} = \frac{\text{Zircon+Tourmaline+Rutile}}{\text{Total No.of Non opaque heavy minerals}}$$

This formula is referred to as Hubert’s (1962) scheme. The calculated index is expressed in percentage to ascertain the mineralogical maturity of the sediment. Accordingly, ZTR <75% implies immature to sub mature sediments and ZTR >75% indicates mineralogically matured sediments. The ZTR Index calculated from the result of heavy minerals analysis for the selected five samples varies from 46.67-58.82%. Majority of the sample locations have >50% ZTR index. Only one sample has <50% ZTR index (sample code 2B). Therefore, the ZTR indices suggest that almost all the sediments are mineralogically immature to sub mature. The geochemical results indicate 3.17 ratios of SiO_2/Al_2O_3 and 0.50 ratios of Na_2O/K_2O. These values, according to Jenner et al. (1988) are indicative of high chemically stable minerals in the sandstone and depict mineralogical maturity of the sandstone. The average values of log SiO_2 / Al_2O_3 (0.47) in samples is less than 1.5 and average values of the log K_2O/Na_2O (-0.35) is less than 0 (Table 6). Furthermore, the average values of the log Fe_2O_3+MgO/Na_2O is more than 0. The low alkalis values in all the studied samples indicate mature sandstone. The depletion of Na_2O (<1%) in all samples (Table 6) can be attributed to a relatively smaller amount of Na-rich plagioclase in the sandstone samples. The enrichment of silica (quartz) over Al_2O_3 (i.e. log SiO_2/Al_2O_3 < 1.5) is a reflection of the duration and intensity of weathering and destruction or dissolution of other minerals during transportation. These indicate that Lokoja Sandstones had undergone long period of transportation and intense weathering resulting in the destruction of other minerals (especially plagioclase and potassium feldspars) during transportation. The geochemical datasets shown in Tables 5 and 6 consequently depicted Lokoja Sandstones are mature lithic arenites including sub-greywacke and protoquartzites.

4.3 Weathering of the source area

The chemical index of alteration (CIA = 100 x Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O) have been established as a general indicator of the degree of weathering in any provenance regions (Nesbitt and Young, 1982). In the equation given above, CaO* is the amount of CaO incorporated in the silicate fraction of the studied sandstone samples. Correction for CaO from carbonate contribution was not done for the studied sandstone samples since there was no CO_2 data. Consequently, to compute for CaO* from the silicate fraction, the assumption proposed by Bock et al. (1998) was adopted. In this regard, CaO values were accepted only if CaO ≤ Na_2O; accordingly, when CaO>Na_2O, it was assumed that the concentration of CaO equals that of Na_2O (Bock et al., 1998). This procedure provides measure of the ratio of the secondary aluminous mineral to feldspar, and forms a basis for the measure of intensity of weathering (Elzien et al., 2014). Low CIA values of approximately 50 imply an unweathered upper crust or weak weathering, but high values (i.e. 76-100) indicate intense weathering with a complete removal of alkali and alkaline earth elements and an increase in Al_2O_3 (McLennan, 1993; Fedo et al., 1995; Dupuis et al., 2006). Table 6 shows average CIA value of 79.37 % suggestive of intense weathering at the source area. Furthermore, the calculation of the mineralogical index of alteration (MIA), according to Voicu et al. (1997) is: MIA = 2*(CIA-50). The different ranges of MIA values are: incipient (0-20%), weak (20-40%), moderate (40-60%), and intense to extreme (60-100%) degree of weathering. The value of 100 % means complete weathering of a primary material into its equivalent weathered product (Voicu and Bardoux, 2002). Table 6 shows MIA average value of 58.74 % which suggests moderate degree of weathering. The CIA and MIA values of Lokoja Sandstone indicate that their source area underwent “intense” recycling but “moderate to high” degree of chemical weathering.

4.4 Provenance and chemical maturity

The discriminant functions diagram of Roser and Korsch (1988) has been used to construct the source of the sediments and provenance of the Lokoja Sandstone (Fig.5). This diagram shows that the plotted sandstones were mostly derived from felsic igneous source.

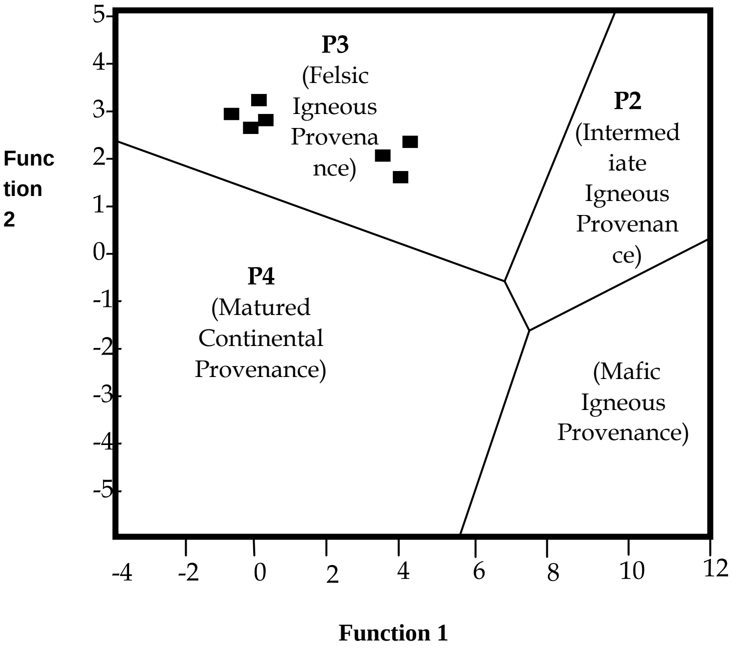

Figure 5: *Plots of discriminant functions 1 and 2 for the Lokoja sandstone (After Roser and Korsch, 1988).*

The low concentrations of Cr and Ni, the ratio of Cr/Ni range between 0.24 and 0.55 (average = 0.42) (Table 7), these probably signify derivation of these elements from felsic igneous rocks. Diagram of Suttner and Dutta (1986) was used in order to classify the maturity of Lokoja sandstone as a function of climate. The plotted samples revealed semi arid to arid conditions for the samples with varied maturity (Fig.6). The studied sandstones have SiO_2 and Al_2O_3 contents averaging 59.80 and 11.52wt% respectively but, as expected; the sandstones have higher SiO_2 and correspondingly lower Al_2O_3. The average of SiO_2/Al_2O_3 ratio of the Lokoja Sandstone which is 3.17 shows detrital influxes dominated by large extent of weathering.

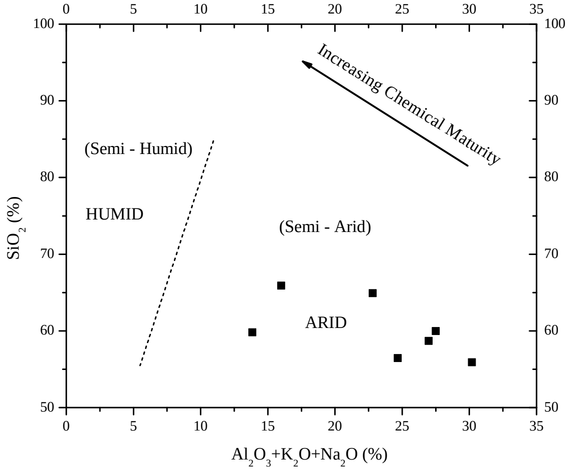

Figure 6: *Chemical maturity of Lokoja Sandstone (Suttner & Dutta, 1986).*

Table 5: Classification of sandstone based on chemical approach (After Blatt et al., 1972; Hebron, 1988; Pettijohn, et al., 1972; Potter, 1978; Akinmosin and Osinowo, 2008; Obiefuna and Orazulike, 2011; Akinyemi et al., 2014).

Serial no.	Log of ratios of oxides	Types of sandstone
1	Log (SiO_2/Al_2O_3) > 1.5	Arenites
2	Log (SiO_2/Al_2O_3) > 1 and log (K_2O/Na_2O)< 0	Greywacke
3	Log (SiO_2/Al_2O_3) > 1.5 and log (K_2O/Na_2O)> 0 and log (Fe_2O_3 + MgO)/Na_2O + K_2O)	Arkose
4	Log (SiO_2/Al_2O_3) > 1.5 and either log (K_2O/Na_2O)< 0 and log (Fe_2O_3 + MgO/Na_2O) > 0	Lithic arenites (including sub-greywacke and protoquartzites

The average of Na_2O/K_2O ratio of the studied sandstone samples is 2.48.. This literally suggests felsic igneous rock source. The large quantity of alkalis (Na_2O and K_2O) characterizes immature sandstones such as Arkoses and greywackes whereas the ratios of Na_2O/K_2O could be used to establish both the provenance and diagenesis of sandstone deposit (Akinmosin and Osinowo, 2008; Ibe and Akaolisa, 2010). Trace elements such as Cr, Ni, Co, and V have been used to determine mafic and ultramafic sources (Wronkiewicz and Condie, 1987; Huntsman-Mapila et al.,2005).

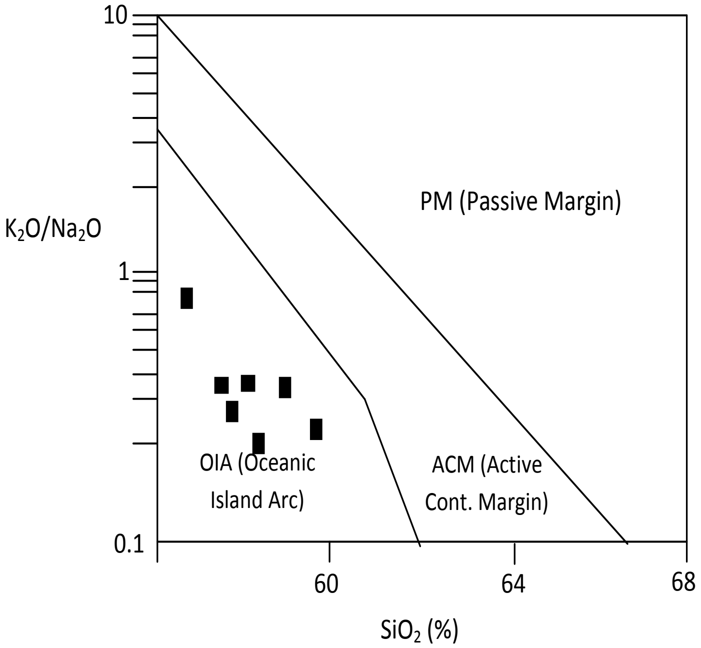

Figure 7: *Discrimination diagram K_2O/Na_2O vs. SiO_2,(Roser and Korsch, 1986) For Lokoja sandstone, (OIA): Oceanic island arc, (ACM): Active continental margin, (PM): Passive margin.*

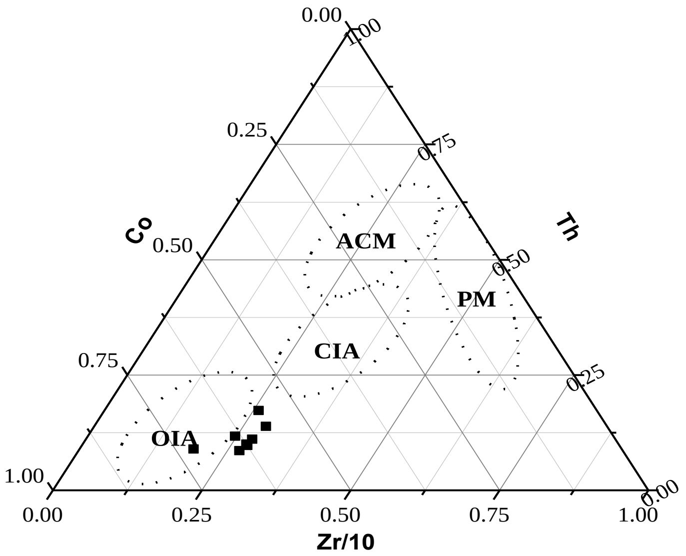

Figure 8: *Tectonic discrimination diagram (i.e. Th-Co-Zr/10 ternary diagram) for Lokoja sandstone (Bhatia and Crook, 1986).*

The average concentrations of the followings trace elements in the studied sandstones are: Cr, 2.22ppm; Co, 1.98ppm; and Ni, 5.69ppm (Table 7). The lower concentrations of Cr, Co, and Ni and higher concentration of Zr, Ba and Sr observed in the sandstones suggest felsic source rock. Felsic source rocks usually contain lower concentrations of Cr, Co, Ni, and V and higher concentrations of Ba, Sr, Y, and Zr than mafic and intermediate source rocks (Wronkiewicz and Condie, 1987; Spalletti et al., 2008). Ratios such as Eu/Eu*, (La/ Lu)cn, La/Sc, Th/Sc, La/Co, Th/Co, and Cr/Th are significantly different in mafic and felsic source rocks and can therefore

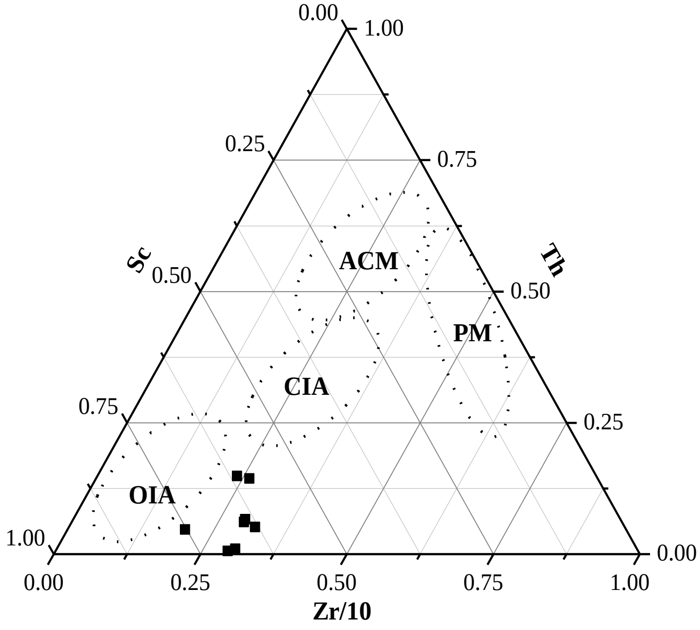

Figure 9: *Tectonic discrimination diagram (i.e. Th-Sc-Zr/10 ternary diagram) for Lokoja sandstone (Bhatia and Crook, 1986).*

provide information about the provenance of sedimentary rocks (Cullers et al., 1988; Wronkiewicz and Condie, 1989; Condie and Wronkiewicz, 1990; Cullers, 1994). Therefore, the lower ratios of Ni/Co, Cr/Ni, Cr/Th, Cr/Sc, Th/Sc, La/Co and Th/Co (Table 7) suggest felsic source rock for the studied Lokoja sandstone.

4.5. Tectonic setting

Several types of discrimination diagrams of tectonic settings that use major oxides composition have been proposed for clastic sediments. The K_2O/Na_2O vs. SiO_2 binary tectonic diagram of Roser and Korsch, (1986) discriminates between oceanic island arc (OIA), active continental margin (ACM) and passive margin (PM) tectonic setting, this diagram classified the Lokoja Sandstone into oceanic island arc (Fig.7). Inert trace elements in clastic sediments have also been used successfully in discrimination diagrams of plate tectonic settings (Varga and Szakmany, 2004; Elzien et al., 2014), these elements are probably transferred quantitatively into detrital sediments during weathering and transportation, reflecting the signature of the parent material (Armstrong - Altrin et al., 2004). The Th-Co-Zr/10 and Th-Sc-Zr/10 ternary diagrams (Bhatia and Crook, 1986) have been used to differentiate between oceanic island arc (OIA), continental island arc (CIA), active continental margin (ACM) and passive margin (PM) settings (Figs. 8 & 9). All the studied samples plotted in the field of oceanic island arc (OIA).

5. Conclusion

The composition, provenance, weathering, tectonic setting and redox proxy of the Lokoja sandstone, Middle Niger basin has been assessed using integrated petrographic, granulometric and geochemical approach. Major elements geochemistry and their ratios revealed that the Lokoja sandstone is mostly mature lithic arenites including sub-greywacke and protoquartzites influence of felsic igneous provenances on the passive basin. The heavy mineral suites are indicative of igneous and metamorphic sources, perhaps, the southwest and north central Basement Complex terrains. The calculated mineral maturity index (MMI) and ZTR indices suggest mineralogically immature to sub mature sediments. The grain size distribution results suggest medium to coarse grained sediments were positively coarsely skewed and leptokurtic. Accordingly implying river deposited sediments under low energy current. The source area is recognised by semi arid to arid conditions resulted moderate to strong weathering affecting due to CIA and MIA values. The source materials tectonically may deposit in an oceanic island arc. Further similar studies may use the interrelationships of MMI, ZTR and major elements ratios to make a clear decision on the mineralogical maturity of clastic sediments.

6. Acknowledgements

The authors wish to express their gratitude for the technical assistance of the final year students who participated in the fieldwork (Sedimentary/Petroleum Geology option 2011/2012 session). Ms. Melissa Crowley, XRF laboratory in the University of the Western Cape, South Africa for XRF analysis, and Ms. Riana Rossouw, LA-ICP-MS laboratory in the University of Stellenbosch for multi-element analysis.

REFERENCES

[1] Adeleye, D. R. Sedimentology of the fluvial Bida Sandstones (Cretaceous) Nigeria. Sedimentary Geology, 1972; 12, 1-24.

[2] Agyingi, C.M., Geology of upper Cretaceous rocks in the eastern Bida Basin, Central Nigeria. Unpublished Ph.D. Thesis, University of Ibadan, Nigeria, 1991; 501pp.

[3] Akinmosin, A., and Osinowo, O.O. Geochemical and mineralogical composition of Ishara sandstone deposit. SW Nigeria Cont. J. Earth Sci., 2008; 3, 33-39.

[4] Akintola, A.I., Ikhane, P.R., Okunlola, O. A., Akintola, G.O., Oyebolu, O.O., and Owoseni, F.R. Mineralogical and geochemical studies of sandstone in Imobi study area and its environs, southwestern Nigeria. Journal of Environment and Earth Science, 2012; 2, 93-105.

[5] Akinyemi, S. A., Adebayo, O. F., Ojo, A. O., Fadipe, O. A., Gitari, W. M. Geochemistry and mineralogy of the Campanian Sandstone of Lokoja-Basange Formation, Middle Niger Basin (Lokoja sub-basin), Nigeria: Implications for provenance, weathering, tectonic setting and paleo-redox condition. Journal of Natural Sciences Research, 2014; 4, No.16, 65 – 89.

[6] Al-Juboury, A. Petrography and major element geochemistry of Late Triassic Carpathian Keuper sandstones: Implications for provenance. Bulletin de l’Institut Scientifique, Rabat, section Sciences de la Terre, 2007; no. 29, 1-14.

[7] Armstrong-Altrin, J.S., Lee, Y.I., Verma, S.P., Ramasamy, S. (2004). Geochemistry of sandstones from the upper Miocene kudankulam Formation, southern India: Implication for provenance, weathering and tectonic setting. Journal of sedimentary Research, 74(2), 285 – 297.

[8] Armstrong-Altrin, J.S., Verma, S. P. Critical evaluation of six tectonic setting discrimination diagrams using geochemical data of Neogene sediments from known tectonic settings. Sedimentary Geology, 2005; 177, 115–129.

[9] Bhatia, M.R., and Crook. K.A.W. Trace element characteristics of greywackes and tectonic setting discrimination of sedimentary basins. Contrib. Mineral. Petrol. 1986; 92, 181–193.

[10] Bhatia, M. R., and Crook, A. W. Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. Contributions to Mineralogy and Petrology, 1986; 92, 181–193.

[11] Bock, B., McLennan, S.M., Hanson, G.N. Geochemistry and provenance of the Middle Ordovician Austin Glen Member (Normanskill Formation) and the Taconian Orogeny in New England. J. Sediment., 1998; 45, 635–655.

[12] Braide, S. P. Syntectonic fluvial sedimentation in the central Bida Basin. Journal of Mining and Geology, 1992b; 28, 55-648.

[13] Braide, S.P. Geological development, origin and energy mineral resource potential of the Lokoja Formation in the southern Bida Basin. Journal of Mining and Geology, 1992a; 28, 33-44.

[14] Condie, K.C., Boryta, M.D., Liu, J., Quian, X. The origin of khondalites: geochemical evidence from the Archean to Early Proterozoic granulitic belt in the North China Craton. Precambrian Research, 1992; 59, 207-223.

[15] Cullers, R. L. The controls on the major and trace element evolution of shales, siltstones and sandstones of Ordovician to Tertiary age in the Wet Mountain region, Colorado, U.S.A. Chemical Geology, 1995; 123, 107-131.

[16] Dessauvagie, T. F. G. (1975). Explanatory note to the geological map of Nigeria, scale 1: 1,000,000. Jour. Min. and Geol. (Nig. Min. Geol. And Met. Soc.), 9 (1 2), 3 28.

[17] Dickson, W.R., Suczek, C. A. Plate tectonics and sandstone compositions: American Association of petroleum Geologist, 1979; 63, 2164 – 2182.

[18] Dupuis, C, Hebert, R, Cote, VD, et al.”Geochemistry of sedimentary rocks melange and flysch units south of the YarlungZangbo suture zone, southern Tibet”. Journal of Asian Earth Sciences, 2006; 26, 489-508.

[19] Elzien, S.M.; Farah, A. A. Alhaj, A. B.; Mohamed, A.A.; Al-Imam, O.A. O., Hussein, A. H.; Khalid, M. K., Hamed, B.O.; Alhaj, A. B. Geochemistry of Merkhiyat Sandstones, Omdurman Formation, Sudan: Implication of depositional environment, provenance and tectonic setting. International Journal of Geology, Agriculture and Environmental Sciences Volume – 2 Issue – 3 :10-15.

[20] Folk, R.L., and Ward, W.O. Brazos river bar: a study in the significance of grain size parameters. Journal of sedimentary petrology, 1957; vol.27, Pp. 3-26

[21] Friedman, G.M. Differences in size distribution of population of particles among sands of various origins, sedimentology, 1969; vol. 26, p. 3-32.

[22] Gideon, Y. B., Fatoye, F. B., and Omada, J. I. Sedimentological Characteristics and Geochemistry of Ajali Sandstone Exposed at Ofe-Jiji and Environs, Northern Anambra Basin, Nigeria. Research Journal of Environmental and Earth Sciences, 2014; 6(1), 10-17.

[23] Hebron, M.M. Geochemical classification of terrigenous sands and shales from core or log data. Journal of Sedimentary Petrology, 1988; 58, 820-829.

[24] Hubert, J. T. Zircon-tourmaline-rutile maturity index and interdependence of the composition of heavy minerals assemblages with the gross composition and texture of sandstones. J. Sed pet., 1962; 32:440–450.

[25] Huntsman-Mapila, P., Kampunzu, A.B., Vink, B., et al. Cryptic indicators of provenance from the geochemistry of theOkavango Delta sediments, Bostwana”. Sedimentary Geology, 2005; 174, 123-148.

[26] Ibe, K.K., and Akaolisa, C.C.Z. Sand classification scheme for Ajali sandstone units in Ohafia area. SE Nigeria J. Geol. Min. Res., 2010; 2(1), 16-22.

[27] Idowu, J.O. and Enu, E.I. Petroleum geochemistry of some Late Cretaceous Shales from the Lokoja Sandstone of Middle Niger Basin, Nigeria. Journal of African Earth Sciences, 1992; v.14, p.443-455.

[28] Igwe, E. O., Amoke, G. U. & Ngwu, C. N. Provenance and Tectonic Setting of Amasiri Sandstone (Turonian) in Ugep Area, Southern Benue Trough, Nigeria: Evidences from Petrography and Geochemistry. Global Journal of Science Frontier Research Environment & Earth Science, 2013; Volume 13 Issue 2 Version 1.0: 32-40.

[29] Ikhane, P. R., Akintola, A. I., Bankole, S. I., Oyebolu, O. O. and Ogunlana, E. O. Granulometric analysis and heavy mineral studies of the sandstone facies exposed near Igbile, southwestern Nigeria. International Research Journal of Geology and Mining (IRJGM) (2276-6618), 2013;Vol. 3(4) pp. 158-178.

[30] Ikhane, P.R., Omosanya, K.O., and Owoseni, F.R. Provenance studies of sandstone in Imobi and its environs south western Nigeria. International Journal of Current Research, 2011; 3, 344-350.

[31] Jafarzadeh, M., and Hosseini-Barzi, M. Petrography and geochemistry of Ahwaz Sandstone Member of Asmari Formation, Zagros, Iran: implications on provenance and tectonic setting. Revista Mexicana de Ciencias Geológicas, 2008; 25, 247-260.

[32] Jan Du Chene, R. E., Klasz, I.D.E., Archibong, E. E. Biostratigraphic study of the borehole Ojo-1, SW Nigeria, with special emphasis on the Cretaceous Microfloral. Revue de Micropaleontology, 1979; 21, 123-139.

[33] Jenner, G.A., Firyery, B.J. and McLennan, S.M. Geochemistry of Archean yellow knife super group geochemistry. Cosmachim. Acta, 1988; 45(2): 19-23.

[34] Jones, H. A. The oolitic ironstone of Agbaja Plateau, Kabba Province. Record of the Geological survey of Nigeria, 1955; pp.20 – 43.

[35] Kennedy, W. Q. The influence of basement structure on the evolution of the coastal (Mesozoic and Tertiary)

basins. In: Recent Basins around Africa. Proceedings of the Institute of Petroleum Geologists Society, London, 1965; pp. 35-47.

[36] King, L. C. Outline and distribution of Gondwanaland. Geological Magazine, 1950; 87, 353-359. http://dx.doi.org/10.1017/S0016756800077311.

[37] Kogbe, C. A. Geological Interpretation of Landsat Imagery of part of Central of central Nigeria. Journal of Mining and Geology, 1981; 28, 66-69.

[38] Kogbe, C. A., Ajakaiye, D. E., & Matheis, G. Confirmation of rift structure along the middle- Niger Valley, Nigeria. Journal of African Earth Sciences, 1983; 1, 127-131.

[39] McLennan S. M., Rare earth elements in sedimentary rocks: influence of the provenance and sedimentary process, in: Geochemistry and Mineralogy of Rare Earth Elements, 1989; 21, 169-200.

[40] McLennan, S.M.”Weathering and global denudation”. Journal of Geology, 1993; 101, 295- 303.

[41] Nwajide, C.S., and Hoque, MProblem of classification and maturity. Evaluation of a diagno- stically altered fluvial Sandstone. Geologic on Nujibouw, 1985; vol.64 p 67-70.

[42] Obaje, N. G., Musa, M. K. Odoma, A. N. and Hamza, H. The Bida Basin in north-central Nigeria: sedimentology and petroleum geology. Journal of Petroleum and Gas Exploration Research, 2011; Vol. 1(1) pp. 001-013.

[43] Obaje, N.G., Wehner, H., Scheeder, G., Abubakar. M. B., Jauro, A. Hydrocarbon prospectivity of Nigeria’s inland basins: from the view point of organic geochemistry and organic petrology. American Association of Petroleum Geologist Bull., 2004; 87: 325-353.

[44] Obiefuna, G.I., and Orazulike, D. M. Geochemical and Mineralogical Composition ofBima Sandstone Deposit, Yola Area, NE Nigeria. Research Journal of Environmental and Earth Sciences, 2011; 3(2), 95-102.

[45] Ojo SB, Ajakaiye DE (1989). Preliminary interpretation of gravity measurements in the Mid-Niger Basin area, Nigeria. In: Kogbe, C.A. (Ed.), Geology of Nigeria. 2nd edition,Elizabethan Publishers, Lagos, pp. 347–358.

[46] Ojo, O. J. and Akande, S.O., Sedimentological and palynological studies of the Patti Formation, South-eastern Bida Basin, Nigeria: Implications for paleoenvironments and paleogeography. Nig. Ass. Pet. Expl. Bull., 2006; V.19, no.1, p. 61-77.

[47] Ojo, O. J., Akande, S.O. Microfloral assemblage, age and paleoenvironment of the Upper Cretaceous Patti Formation, southeastern Bida Basin, Nigeria. Journal of Mining and Geology; 2008; 44: 71-78.

[48] Ojo, S.B. Middle Niger Basin revisited: magnetic constraints on gravity interpretations. Abstract, 20th Conference of the Nigeria Mining and Geosciences Society, Nsukka, 1984; pp. 52–53.

[49] Ojo, S.B. and Ajakaiye, D.E. Preliminary interpretation of gravity measurements in the Middle Niger Basin area, Nigeria. In C.A. Kogbe (editor) Geology of Nigeria, 1976; pp. 295 – 307.

[50] Omali, A.O., Imasuen, O.I and Okiotor, M. E. Sedimentological Characteristics of Lokoja Sandstone Exposed At Mount Patti, Bida Basin, Nigeria. Advances in Applied Science Research, 2011; 2 (2), 227-245.

[51] Osokpor, J., and Okiti, J. Sedimentological and Paleodepositional Studies of Outcropping Sediments in Parts of Southern Middle Niger Basin. International Journal of Science and Technology, 2013; Vol. 2, 840-846.

[52] Ronov, A.B., Balashov, Y.A., Girin, Y.P., Bratishko, R.K.H., Kazakov, G.A. Regularities of rare earth element distribution in the sedimentary shell and in the crust of the earth. Sedimentology, 1974; 21, 171–193.

[53] Roser, B.P., and Korsch, R.J. Provenance signatures of sandstone–mudstone suites determined using discriminant function analysis of major-element data: Chemical Geology, 1988; 67, 119-139.

[54] Roser, B.P., and Korsch, R. J. Determination of tectonic setting of sandstones-mudstones suites using SiO_2 content and K_2O/Na_2O ratio: Journal of Geol., 1986; 94, 635-650.

[55] Spalletti, L.A., Queralt, I., Matheos, S.D., et al.”Sedimentary petrology and geochemistry of siliciclastic rocks from the upper Jurassic Tordillo Formation (Neuquen Basin, western Argentina): Implications for provenance and tectonic setting”, Journal of South American Earth Sciences, 2008; 25, 440-463.

[56] Suttner, L. J., and Dutta, P. K.. Alluvial sandstone composition and paleoclimate. I. Framework mineralogy. J. Sed. Petrol. 1986; 56, 329–345.

[57] Taylor, S. R., and McLennan, S. M. The Continental Crust: its Composition and Evolution: An Examination of the Geological Record Preserved in Sedimentary Rocks: Oxford, U.K., Blackwell, 1985; 328 pp.

[58] Tijani, M. N., Nton, M. E., Kitagawa, R. Textural and geochemical characteristics of the Ajali Sandstone, Anambra Basin, SE Nigeria: Implication for its provenance. Comptes Rendus Geoscience, 2010; 342, 136–150.

[59] Valloni, R., Mezzardi, G. Compositional suites of terrigenous deep sea sands of the present continental margins: Sedimentology, 1984; 31, 353–364.

[60] Voicu, G., and Bardoux, M. Geochemical behaviour under tropical weathering of the Barama-Mazaruni greenstone belt at Omai gold mine, Guiana Shield. Applied Geochemistry, 2002; 17, 321-336.

[61] Voicu, G., Bardoux, M., Harnois, L., and Grepeau, R. Lithological and geochemical environment of igneous and sedimentary rocks at Omai gold mine, Guyana, South America. Exploration and Mining Geology, 1997; 6, 153-170.

[62] Whiteman, A.J. Nigeria. Its Petroleum Geology, Resources and Potential. Graham and Trotman, London, 1982; 399p.

[63] Wronkiewicz, D.J., and Condie, K.C. Geochemistry and provenance of sediments from the Pongola Supergroup, South Africa: Evidence for a 3.0-Ga-old continental Craton: Geochimica et Cosmochimica Acta, 1989; 53, 1537–1549.

[64] Wronkiewicz, D.J., Condie, K.C. Geochemistry of Archean shales from the WitwaterslandSupergroup, South Africa: source area weathering and provenance. Geochimica et Cosmochimica Acta, 1987; 51, 2401- 2416.

[65] Wronkiewicz, D. J., Condie, K. C. Geochemistry and mineralogy of sediments from the Ventersdorp and Transvaal Supergroups, South Africa: Cratonic evolution during the Early Proterozoic. Geochim. Cosmochim. Acta, 1990; 54, 343–354.

Table 6: Major elements concentrations (wt %) for outcropping Lokoja sandstones.

Sample no	SiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	CIA	MIA
A1	56.40	22.50	6.50	0.02	3.60	1.26	0.92	1.08	1.48	0.11	79.56	59.12
A2	56.39	21.68	7.78	0.02	3.53	1.29	0.97	1.06	1.44	0.24	78.92	57.84
B1	64.95	21.58	5.31	0.01	1.69	5.04	0.96	1.25	2.70	0.11	73.73	47.45
B2	64.90	20.65	8.58	0.01	3.02	1.52	0.64	3.22	0.77	0.55	79.95	59.89
C1	65.90	10.83	6.49	0.02	1.77	4.21	0.96	1.20	2.68	0.45	60.95	21.89
C2	58.69	25.23	6.25	0.02	1.70	1.2	0.55	1.04	1.30	0.22	87.97	75.94
D1	56.45	22.48	7.70	0.02	3.65	1.28	0.91	1.20	2.68	0.24	79.38	58.76
D2	55.90	28.2	5.80	0.01	1.54	1.32	0.68	2.42	1.64	0.11	88.85	77.69
E1	59.96	25.66	7.63	0.01	0.46	1.38	0.47	1.22	2.57	0.43	91.74	83.48
E2	59.80	11.52	6.60	0.02	2.00	1.45	0.88	1.23	1.28	0.44	72.68	45.36
Average	59.93	21.03	6.86	0.02	2.30	2.00	0.79	1.49	1.85	0.29	79.37	58.74

Sample no	Al_2O_3/TiO_2	K_2O+Na_2O	SiO_2/Al_2O_3	MgO/CaO	Na_2O/K_2O	TiO_2/Zr	Fe_2O_3/K_2O	Fe_2O_3+MgO	$Log(SiO_2/Al_2O_3)$	$Log(K_2O/Na_2O)$	$Log(Fe_2O_3+MgO/Na_2O)$	$Log(Fe_2O_3+MgO/K_2O+Na_2O)$
A1	20.83	2.18	2.51	0.41	1.37	75.52	7.07	7.98	0.40	-0.14	0.89	0.97
A2	20.45	2.26	2.60	0.41	1.33	78.40	8.02	9.22	0.42	-0.12	0.95	1.02
B1	17.26	6.00	3.01	1.60	5.25	110.33	5.53	8.01	0.48	-0.72	0.77	1.12
B2	6.41	2.16	3.14	0.25	2.38	323.94	13.41	9.35	0.50	-0.38	0.96	1.05
C1	9.03	5.17	6.08	1.51	4.39	126.05	6.76	9.17	0.78	-0.64	0.85	1.13
C2	24.26	1.75	2.33	0.76	2.18	105.16	11.36	7.55	0.37	-0.34	0.87	0.99
D1	18.73	2.19	2.51	0.73	1.41	106.19	8.46	10.38	0.40	-0.15	0.99	1.08
D2	11.65	2.00	1.98	1.06	1.94	209.71	8.53	7.44	0.30	-0.29	0.85	0.98
E1	21.03	1.85	2.34	5.59	2.94	137.85	16.23	10.20	0.37	-0.47	0.98	1.16
E2	9.37	2.33	5.19	0.64	1.65	136.21	7.50	7.88	0.72	-0.22	0.87	0.98
Average	15.90	2.79	3.17	1.30	2.48	140.94	9.29	8.72	0.47	-0.35	0.90	1.05

Chemical index of alteration (CIA, Nesbitt and Young, 1982) and Mineralogical index of alteration (MIA, Voicu et al., 1997).

Table 7: Trace elements concentrations (ppm) for outcropping Lokoja sandstones.

Sample no	Pb	As	Cd	Cr	Th	Cu	N i	Sc	Co	Hg	Ba	Ca	La	Sr	Zr
A1	1.88	1.59	1.00	2.02	5.45	14.20	8.40	1.80	2.14	1.90	201.00	30.10	17.00	67.20	143.00
A2	1.86	1.52	1.20	2.05	2.64	14.90	8.64	1.52	2.42	1.25	200.00	26.60	19.10	62.00	135.20
B1	1.50	1.52	1.00	2.5	4.30	12.70	6.50	0.83	2.34	1.65	199.00	20.00	14.10	68.00	113.30
B2	1.23	1.22	1.00	2.33	5.01	10.40	4.72	0.81	2.40	1.83	201.00	22.20	12.40	55.20	99.40
C1	1.58	1.24	1.40	2.41	4.34	12.70	4.40	0.90	2.90	1.60	156.00	20.90	14.60	61.90	95.20
C2	1.62	1.46	1.00	2.15	3.85	10.00	4.70	2.40	1.83	1.90	122.00	21.00	15.10	60.30	98.90
D1	1.55	1.22	1.32	2.08	3.01	12.30	5.60	0.70	1.41	1.24	99.00	18.40	12.70	55.40	113.00
D2	1.50	1.22	1.00	2.49	4.85	12.70	4.50	0.10	1.54	1.25	116.00	16.40	14.20	58.40	115.40
E1	1.14	1.28	1.30	2.03	3.90	12.60	4.76	2.14	1.42	1.27	102.00	14.30	12.60	60.20	88.50
E2	1.21	1.22	1.10	2.12	4.02	10.40	4.72	0.13	1.40	2.87	96.00	14.10	12.00	58.20	90.30
Average	1.51	1.35	1.13	2.22	5.01	12.29	5.69	1.13	1.98	1.68	139.2	20.00	17.06	60.68	109.22

Trace element ratios

Sample no	Ni/Co	Th/Co	La/Co	Th/Co	Cr/Ni	Cr/Sc	Cr/Th	Th/Cr	Zr/Sc	La/Sc	Th/Sc	Sc/Th
A1	3.93	2.55	7.94	2.55	0.24	1.12	0.37	2.70	79.44	9.44	3.03	0.33
A2	3.57	1.09	7.89	1.09	0.24	1.35	0.78	1.29	88.95	12.57	1.74	0.58
B1	2.78	1.84	6.03	1.84	0.38	3.01	0.58	1.72	136.51	16.99	5.18	0.19
B2	1.97	2.09	5.17	2.09	0.49	2.88	0.47	2.15	122.72	15.31	6.19	0.16
C1	1.52	1.50	5.03	1.50	0.55	2.68	0.56	1.80	105.78	16.22	4.82	0.21
C2	2.57	2.10	8.25	2.10	0.46	0.90	0.56	1.79	41.21	6.29	1.60	0.62
D1	3.97	2.13	9.01	2.13	0.37	2.97	0.69	1.45	161.43	18.14	4.30	0.23
D2	2.92	3.15	9.22	3.15	0.55	24.90	0.51	1.95	1154.00	142.00	48.50	0.02
E1	3.35	2.75	8.87	2.75	0.43	0.95	0.52	1.92	41.36	5.89	1.82	0.55
E2	3.37	2.87	8.57	2.87	0.45	16.31	0.53	1.90	694.62	92.31	30.92	0.03
Average	2.99	2.21	7.60	2.21	0.42	5.71	0.56	1.87	262.60	33.52	10.81	0.29