



Sedimentology and Hydraulic Conductivity of Outcropping Sandstone Facies of the Lokoja Formation at Koton-Karfe, Southern Bida Basin, Nigeria

Olumayowa Temitope Ijaleye^{1*}, Daniel Opemipo Obasaju¹, Abigail Enyojo Jonah¹ and Joy Usman¹

¹Department of Earth Sciences, Prince Abubakar Audu University, Anyigba, Nigeria.

*Corresponding author: mayoajala@yahoo.com

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Abstract

This study investigates the sedimentological characteristics and hydraulic conductivity of sandstone facies of the Lokoja Formation exposed at Koton-Karfe in the Southern Bida Basin, Nigeria. The study aims to evaluate the grain-size distribution, mineral composition, and permeability of the outcropping sandstone in order to assess its reservoir potential. Methods employed include sieve analysis, petrographic examination, and permeability testing. Results from sieve analysis indicate that the sediments are predominantly medium- to coarse-grained, poorly sorted, very positively skewed, and very platykurtic. Petrographic analysis reveals that quartz and feldspar are the dominant minerals, with quartz occurring in the highest proportion. The mineral composition suggests that the sediments were derived mainly from volcanic-plutonic rocks or pre-existing sedimentary sources. The presence of feldspar and poor sorting indicates that the sandstones are both mineralogically and texturally immature. Permeability test results indicate low hydraulic conductivity, suggesting poor reservoir characteristics. These findings give insight into the depositional environment and reservoir quality of the Lokoja Formation sandstones in the study area.

Keywords: Sediments, hydraulic conductivity, sorting, porosity, permeability

Introduction

Sandstones are important reservoir rocks for oil, gas, and groundwater. This is because of their generally favorable porosity and permeability characteristics. The geometry, architecture, and spatial distribution of sand bodies are largely controlled by the depositional environment, which ultimately governs reservoir heterogeneity and performance (Ijaleye *et al.*, 2025). Different depositional settings, such as fluvial, deltaic, or marine environments, produce variations in grain size, sorting, and sedimentary structures, all of which influence reservoir quality (Zongquan *et al.*, 2025).

The storage and transmission of groundwater are primarily influenced by the hydraulic conductivity and porosity of the medium. Primary porosity is generally controlled by grain orientation, sorting, and packing, while the angularity of sediments may either enhance or reduce porosity depending on particle size and arrangement (Agbotui *et al.*, 2025). Well-sorted sediments typically exhibit higher porosity compared to poorly sorted sediments, as finer grains in poorly sorted sediments tend to fill the voids between larger grains, thereby reducing pore space (Zhang *et al.*, 2024).

In addition to depositional controls, post-depositional processes (diagenesis) significantly modify reservoir properties. Processes such as compaction, cementation, dissolution, and recrystallization can either reduce or enhance porosity and permeability (Zongquan *et al.*, 2025). For instance, compaction and cementation generally decrease porosity by reducing pore volume, whereas dissolution of unstable minerals may create secondary porosity, thereby improving reservoir quality.

Agents of cementation in sedimentary rocks reduce primary porosity by occupying void spaces within the rock framework. Effective porosity, defined as the interconnected pore spaces that contribute to fluid flow, is more relevant in hydrogeological and petroleum studies than total porosity (Agbotui *et al.*, 2025). This interconnection permits fluids to move from one point to another within body of rock.

Permeability, which is closely related to effective porosity, describes the ability of a rock to transmit fluids through its pore network. It is influenced not only by pore size and connectivity but also by grain size distribution, pore throat geometry, and the presence of fractures (Liu *et al.*, 2024). High porosity does not necessarily imply high permeability, as poorly connected pore spaces may restrict fluid flow.

Furthermore, anisotropy and heterogeneity within sandstone reservoirs can significantly influence fluid flow behavior. Variations in sediment layering, grain alignment, and structural features may result in directional differences in permeability, which are important in reservoir evaluation and groundwater studies (Yang *et al.*, 2025).

Together, porosity and permeability are fundamental parameters used to investigate reservoir quality, as they estimate both the storage capacity and flow efficiency of fluids within the rock. A comprehensive understanding of these properties is therefore essential for effective groundwater exploitation, hydrocarbon recovery, and reservoir management.

This study aims to determine the porosity and permeability of the rock samples, in order to make informed inferences about the reservoir quality, and fluid flow characteristics of the sediments being investigated.

Experimental Methods

Site Description

The study area falls within the Lokoja Formation of the Southern Bida Basin of Nigeria. It lies within latitudes $N8^{\circ}05'45''$ and $N8^{\circ}05'46''$ and longitudes $E6^{\circ}47'34''$ and $E6^{\circ}47'44''$ (Figure 1). It covers a total area of about 29,100 m².

and falls within the Koton-karfe SE topographic map (sheet 227). It is accessible through the major road that links Abuja to Lokoja (Abuja-Lokoja road). The study area is characterized by steep topography with elevation ranging from 40 to 140 m.



Figure 1

Location map of the study area in the Southern Bida Basin

Geology of the study area

The Lokoja Formation, the oldest stratigraphic series in the Southern Bida Basin, unconformably covers the Precambrian Basement Complex, where the study area is located. It is composed of quartz, feldspar, pebbles, cobbles, basal conglomerate, and sub-rounded to well-rounded quartz, particularly near the sediment-basement contact. The conglomerates contain a white clayey matrix. Fine- to extremely coarse-grained conglomeratic sandstones, coarse-grained, cross-bedded sandstone, and a few thin oolitic ironstones cover the basal conglomerate. The sandstones are continental deposits that are often poorly sorted and mostly consist of feldspar and quartz, making them immature both mineralogically and texturally (Ojo and Akande, 2003).

Geological investigation

The method of investigation involved intensive fieldwork with equipment such as a base map, Global Positioning System (GPS), compass, clinometers, hammer, sample bags, masking tape, camera, and field notebook. Transverses were taken, and directional bearings were obtained with the aid of a compass along major roads and minor footpaths. Rock sections were logged, and sampling of rock units was carried out.

Laboratory and data analysis

Fresh samples were carefully collected from each section for laboratory analysis. A total of twenty (20) sandstone samples, each weighing 100 g, were collected for grain-size analysis. Grain-size distribution was determined using standard sieving techniques, and statistical parameters including graphic mean, graphic standard deviation (sorting), inclusive graphic skewness, and graphic kurtosis were calculated following the graphical method (Folk and Ward, 1957). The obtained results were compared to the standard values of these parameters. The following graphical parameters were obtained using (Folk and Ward, 1957) formulae:

$$\text{i. Graphic mean } M_z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$$

$$\text{ii. Graphic Standard Deviation (sorting)} = \sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$$

$$\text{iii. Inclusive Graphic Skewness =SKI} = \frac{(\phi_{84} + \phi_{16} - 2\phi_{50})}{2(\phi_{84} - \phi_{16})} + \frac{(\phi_{95} + \phi_5 - 2\phi_{50})}{2(\phi_{95} - \phi_5)}$$

$$\text{iv. Graphic Kurtosis } K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})}$$

For petrographic and hydraulic conductivity analyses, 12 representative samples were selected from the total collection. Thin sections were prepared and examined under a petrographic microscope using both plane-polarized light (PPL) and cross-polarized light (XPL) to determine mineral composition and textural features. Hydraulic conductivity (K) of each sample was calculated using the equation:

$$K = \frac{aL}{At} \ln \frac{h_1}{h_2} \text{ (cm/s)}$$

where:

a= Cross sectional area of standpipe/burette (cm²)

A= Cross sectional area of soil sample (cm²)

h₁= Hydraulic head across sample at the beginning of test

h₂= Hydraulic head across sample at the end of test

L=Sample length

t=Elapsed time of test (sec)

ln= Natural logarithm

All analyses were performed under controlled laboratory conditions

Results and Discussions

Lithofacies Description and Textural Characteristics

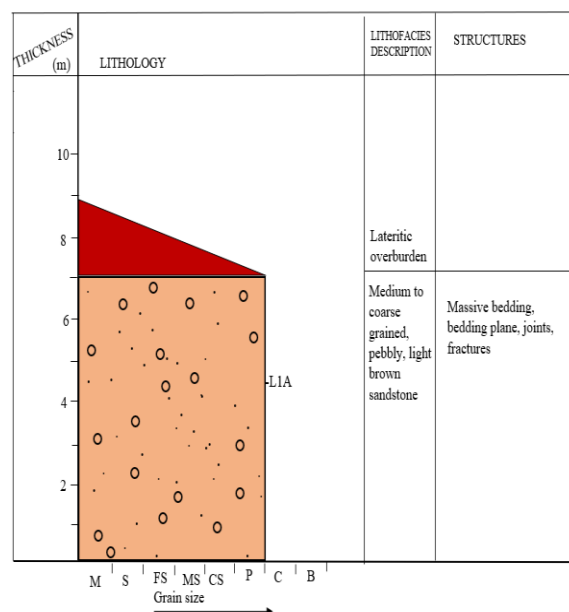
Sandstone facies at location 1

This location is found along the Lokoja-Abuja expressway. The exposed stratigraphic section is located at longitude N08° 05' 45" and latitude E006° 47' 34". It has an elevation of about 40 m, a total thickness of about 8.9 m, and an area extent of approximately 8775 m² (Plate 1, Figure 2). It has only one lithologic unit labeled L1A with a thickness of about 7 m. It is a medium- to coarse-grained, light brown in color, pebbly sandstone. The bed is massive and contains joints and fractures. The overburden is lateritic and about 1.9 m thick.



Plate 1

Exposed stratigraphic section of sandstone facies at location 1 of the study area



Scale: 1cm=1m

Legend: M = Mudstone, S = Siltstone, FS = Fine sand, MS = Medium sand, CS = Coarse sand, P = Pebbles, C = Cobbles, B = Boulder

Figure 2

Lithostratigraphic log of sandstone facies exposed at location 1 of the study area

Sandstone facies at location 2

This location is also found along the Lokoja-Abuja expressway. The exposed stratigraphic section is located at longitude N08° 05' 46" and latitude E006° 47' 34". It has an elevation of about 80 m and a thickness of about 16.5 m (Plate 2, Figure 3). The first lithologic unit is labelled L2A. It has a thickness of about 6.5m. It is a medium to coarse grained, grayish to reddish in color pebbly sandstone. The bed is massive and contains joints and fractures.

Mud cracks are also present. This layer is overlain by a lithologic unit labelled L2B with a thickness of about 5m. It is a medium to coarse grained, reddish in color (ferruginized) pebbly sandstone. The bed is massive and contains joints and fractures. The overburden is lateritic and about 5m thick.



Plate 2
Exposed stratigraphic section of sandstone facies at Location 2 of the study area.

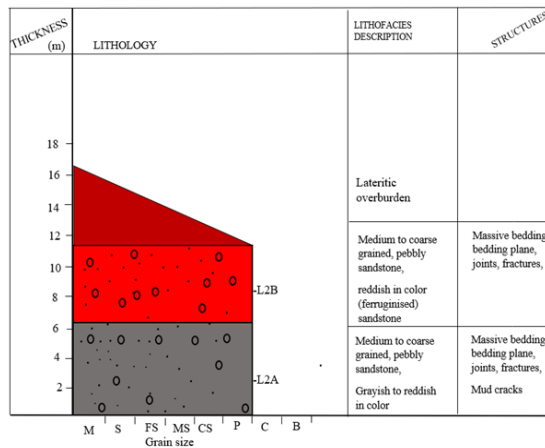


Figure 3
Lithostratigraphic log of sandstone facies exposed at Location 2 of the study area

Petrographic Analysis

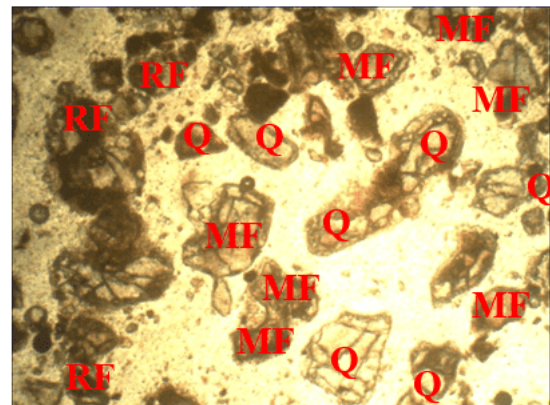
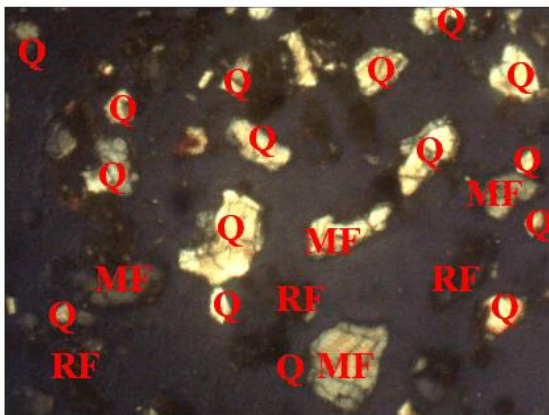
The thin-section study of twelve (12) selected sandstone samples obtained within the study area showed varying proportions of minerals (Table 2). Some of the photomicrographs under plane polarized (PPL) and cross polarized (XPL) lights are as shown in Plates 3a and b. The minerals present in studied sandstone samples are mainly quartz and feldspar. Quartz has the dominant percentage. The minerals generally have shapes ranging from angular to subangular. This implies the deposited sandstone facies are near the source.

Mineral constituents in the collected sandstone samples of the study area have sutural contact, i.e., loosely packed. This suggests that the stage of diagenesis is early, i.e., shallow burial. They also had varied sizes and hence are all poorly sorted. This implied poor porosity and hence low reservoir characteristics. The type of quartz observed in all the sandstone samples was monocrystalline. The copious amount of monocrystalline quartz inferred the provenance of sediments as preexisting sedimentary rock or volcanic-plutonic rock (Molinero-Garcia et al. 2022).

Table2

Mineral composition of collected sandstone samples from thin section study

Sample No.	Quartz (%)	Microcline Feldspar (%)	Mica (%)	Rock Fragments (%)	Total (%)
1	76.34	8.55	6.57	3.94	100
2	77.49	11.71	5.40	3.60	100
3	75.16	12.77	5.73	4.49	100
4	85.84	7.46	2.98	2.23	100
5	72.49	16.05	6.42	2.29	100
6	78.65	7.87	6.18	3.37	100
7	78.34	10.00	5.83	3.33	100
8	79.37	8.47	4.76	4.76	100
9	83.47	6.30	4.72	3.15	100
10	74.18	14.08	6.57	2.35	100
11	73.28	19.83	4.38	2.51	100
12	72.91	18.75	4.94	3.40	100



PPL

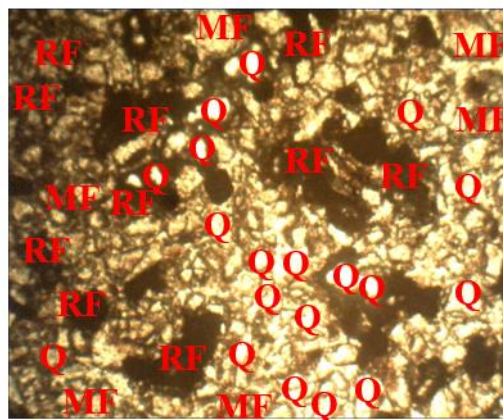
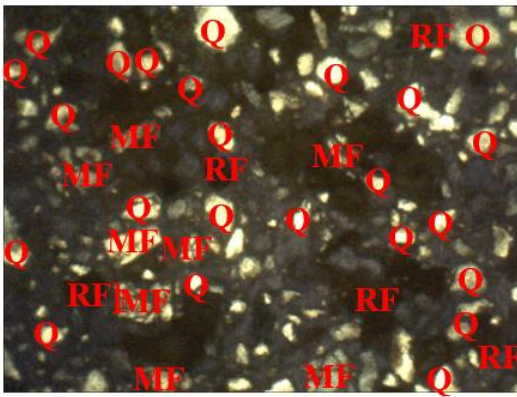
Mg×20

XPL

Plate 3a

Photomicrograph of sample L1A1 under PPL and XPL

Note. Q=quartz, MF= Microcline feldspar and RF= rock fragment



PPL

Mg×20 XPL

Plate 3b

Photomicrograph of sample L2A1 under PPL and XPL

Note. Q=quartz, MF= Microcline feldspar and RF= rock fragment

Sieve analysis

A total of twenty (20) sandstone samples weighing 100 g each was used for this analysis. Cumulative frequency curve is drawn for each sample, A representative of these curves is as shown in figures 4a and 4b.

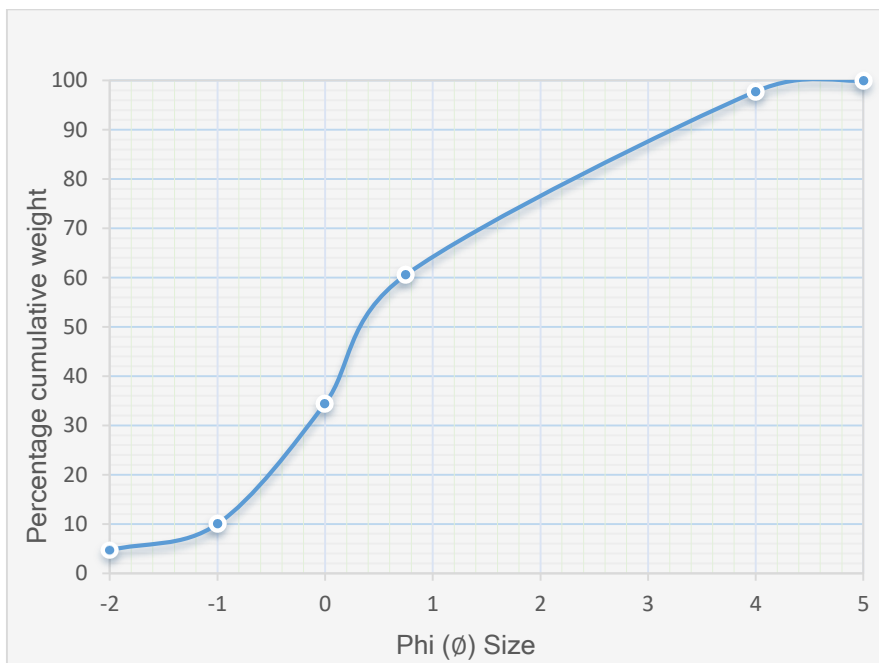


Figure 4a: Cumulative frequency curve of sample L2A1

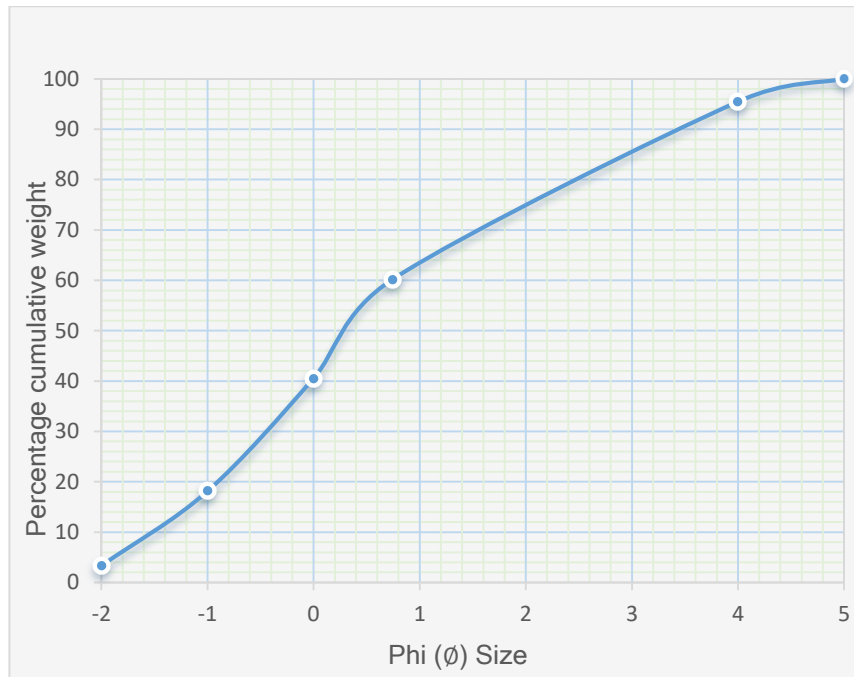


Figure 4.2b: Cumulative frequency curve of sample L2A2

From the comparison of the calculated mean, standard deviation, skewness, and kurtosis with the standard classification (Wentworth, 1922). A summary of grain-size data interpretation is presented in Table 3 and is discussed as follows:

Table 3: Summary of parameters for the grain size analysis of the study area

Sample No	Mean	Sorting	Skewness	Kurtosis	Standard Mean	Standard Sorting	Standard Skewness	Standard Kurtosis
L1A1	1.47	1.45	0.53	0.39	Medium Sand	Poorly Sorted	Very positively skewed	Very Platykurtic
L1A2	1.16	1.08	-0.11	0.29	Medium Sand	Poorly Sorted	Near symmetrical	Very Platykurtic
L1A3	1.56	1.07	0.56	0.29	Medium Sand	Poorly Sorted	Very positively skewed	Very Platykurtic
L1A4	1.36	1.10	0.36	0.42	Medium Sand	Poorly Sorted	Very positively skewed	Very Platykurtic
L1A5	0.73	0.90	0.27	0.51	Coarse Sand	Moderately Sorted	Positively skewed	Very Platykurtic
L1A6	1.27	1.20	0.14	0.36	Medium Sand	Poorly Sorted	Positively skewed	Very Platykurtic
L1A7	0.64	0.83	0.32	0.69	Coarse Sand	Moderately Sorted	Very positively skewed	Platykurtic

Sample No	Mean	Sorting	Skewness	Kurtosis	Standard Mean	Standard Sorting	Standard Skewness	Standard Kurtosis
L1A8	0.80	0.63	-0.16	0.15	Coarse Sand	Moderately Well Sorted	Near symmetrical	Very Platykurtic
L1A9	0.47	0.95	0.50	1.64	Coarse Sand	Moderately Sorted	Very positively skewed	Very Leptokurtic
L1A10	0.83	1.17	0.33	0.59	Coarse Sand	Poorly Sorted	Very positively skewed	Very Platykurtic
L2A1	0.77	1.32	0.43	1.38	Coarse Sand	Poorly Sorted	Very positively skewed	Leptokurtic
L2A2	0.70	1.89	2.02	1.61	Coarse Sand	Poorly Sorted	Very positively skewed	Very Leptokurtic
L2A3	0.83	1.48	0.75	1.19	Coarse Sand	Poorly Sorted	Very positively skewed	Leptokurtic
L2A4	0.97	1.95	1.23	0.05	Coarse Sand	Poorly Sorted	Very positively skewed	Very Platykurtic
L2A5	1.60	0.85	1.13	0.54	Medium Sand	Moderately Sorted	Very positively skewed	Very Platykurtic
L2B1	1.63	1.10	0.57	0.37	Medium Sand	Poorly Sorted	Very positively skewed	Very Platykurtic
L2B2	1.43	1.35	2.11	0.46	Medium Sand	Poorly Sorted	Very positively skewed	Very Platykurtic
L2B3	1.07	0.99	2.48	0.49	Medium Sand	Moderately Sorted	Very positively skewed	Very Platykurtic
L2B4	0.60	0.62	2.68	2.63	Coarse Sand	Moderately Well Sorted	Very positively skewed	Very Leptokurtic
L2B5	1.43	0.88	2.27	0.53	Medium Sand	Moderately Sorted	Very Positively Skewed	Very Platykurtic

The mean grain size in a deposit is largely a function of the energy of processes controlling transport and deposition. The mean was calculated for twenty (20) sandstone samples. The mean grain size for the sandstone samples of the study area ranged from 0.97 Φ (coarse sand) to 1.07 Φ (medium sand) with a total average of 1.11 Φ (medium sand). The coarse and medium sandstone samples are ten (10) in number each. The result showed sediment present is medium to coarse-grained. This is due to the medium to high energy of deposition.

The standard deviation calculated showed sorting values ranging from 0.62 Φ (moderately well sorted) to 1.95 Φ (poorly sorted) with a total average of 1.14 Φ (poorly sorted). Moderately sorted, moderately well sorted and poorly sorted sandstone samples are six (6), two (2) and twelve (12) in number respectively. The moderately well sorted and moderately sorted sediments have grains of fairly the same size and are evidence of sediments

transported far from source while poorly sorted sediments are vice-versa. Majority of the selected sediments being poorly indicated poor reservoir characteristics of the sandstone deposits in the study area (Maju-Oyovwikowhe and Olowu, 2023).

Skewness also shows a reflection of the depositional process. It reflects sorting in the tails of a grain-size population. A population that has a tail of excess fine particles is said to be positively skewed or fine-skewed. i.e., skewed towards positive phi (Φ) values. Populations with a tail of excess coarse particles are negatively skewed or coarse-skewed, i.e., skewed towards negative phi (Φ) values. This is useful in environmental diagnosis because it is directly related to fine and coarse tails of size frequency distribution and hence to the environmental energetics. The skewness values obtained for the twenty (20) selected samples ranges from -0.16Φ (near symmetrical) to 2.27Φ (very positively skewed) with a total average of 0.92Φ (very positively skewed). Very positively skewed, positively skewed and near symmetrical sediments are 16, 2 and 2 in number respectively. Majority of the sediments being positively skewed indicated mostly fine-grained sediments which have poor permeability.

Kurtosis values measures the peakness of a curve from normal. It describes the departure of the distribution from normality by comparing the sorting at the tails with the central position. Sharp-peaked curves are said to be leptokurtic, flat-peaked curves are platykurtic and intermediate between these two curves is mesokurtic. The kurtosis values for the twenty (20) selected sandstone samples ranges from 0.05Φ (very platykurtic) usually poorly sorted to 2.63Φ (very leptokurtic) well sorted with a total average of 0.73Φ (very platykurtic). Very platykurtic, platykurtic, leptokurtic and very leptokurtic samples are 14, 1, 2 and 3 and 2 in number respectively. This indicated majority of the sandstone samples are poorly sorted.

Hydraulic conductivity(K) test

The collected data for the hydraulic conductivity (K) test were carried out on twelve (12) selected soil samples from locations 1 and 2 of the study area. Table 4 shows the estimated hydraulic conductivity (K) values, which were compared with the standard values for interpretation. The estimated K values, which ranged from 1.10×10^{-5} to 7.41×10^{-5} m/s, were obtained for the soil samples. These were inferred to be very fine sands, which are poorly permeable. Poor permeability reduces the ability of a rock to transmit fluid efficiently. Hence, the analyzed sandstone samples have poor reservoir characteristics.

Table 4: *Estimated hydraulic conductivity (K) values of sandstone samples*

Sample No	K (m/s)	Standard Value of Hydraulic Conductivity (K)
1	1.92×10^{-5}	Very fine sands
2	1.48×10^{-5}	Very fine sands
3	7.41×10^{-5}	Very fine sands
4	4.88×10^{-5}	Very fine sands
5	1.10×10^{-5}	Very fine sands
6	2.06×10^{-5}	Very fine sands
7	1.28×10^{-5}	Very fine sands
8	3.99×10^{-5}	Very fine sands
9	1.19×10^{-5}	Very fine sands
10	1.58×10^{-5}	Very fine sands
11	4.98×10^{-5}	Very fine sands
12	5.26×10^{-5}	Very fine sands

Note. Hydraulic conductivity (K) values are estimated from laboratory measurements and compared with standard classifications for fine sands.

Conclusions

The sedimentology and reservoir quality of outcropping sandstone deposits of the Lokoja Formation exposed at Koton-Karfi, Southern Bida Basin, Nigeria, have been investigated. The sieve analysis revealed that the sandstone deposits are medium- to coarse-grained. This is believed to have resulted from medium- to high-energy deposition. It also showed moderately to poorly sorted sediments. These sediments have grains of varying sizes and are evidence of sediments that have been deposited close to the source area i.e., have not undergone much transport. Poor sorting also implies poor porosity and hence low reservoir characteristics. Poor sorting also indicates textural immaturity.

The petrographic analysis revealed quartz and feldspar as the major mineral constituents in the analyzed sandstone deposits with the proportion of quartz being the highest. The analysis also showed that the minerals have shapes ranging from angular to subangular. This implies that the sandstone facies are deposited close to the source. Furthermore, the mineral constituents have loose contact indicating shallow burial. The abundance of monocrystalline quartz, which have clear appearance and euhedral in shape, is indicative of sediments derived from volcanic-plutonic rocks.

The permeability test results showed that the sandstones of the study area are poorly permeable which further confirmed that the sandstones of the study area have poor reservoir characteristics.

Supplementary Material

Not applicable.

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