



# Sedimentological characteristics and mineralogical studies of some Cretaceous sandstones in Nigeria: implications for depositional environment and provenance

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## Abstract

Sedimentological and mineralogical studies from two sandstone formations of pre-Santonian (Awi Formation) and post-Santonian (Lokoja Formation) ages were carried out aiming to characterize their provenance and depositional environments. Detailed field studies, textural and mineralogical analyses involving lithologic descriptions, grain size analysis, thin section, heavy mineral, and X-ray diffraction analyses were carried out. Both sandstones exhibit fining upwards succession and unconformably overlie the basement complex. Other sedimentary structures include grain imbrications, mud drapes, cross stratifications, flaser beds, and ripple marks. Textural studies show that the sandstones have medium to coarse grains and are moderate to poorly sorted, positively skewed, and platykurtic. These characteristics suggest that high-energy conditions prevailed during the deposition of that sandstones. Bivariate analysis of skewness versus sorting showed that the sandstones were deposited in a fluvial environment. Petrographic analysis revealed angular to sub-angular grains with the dominance of quartz and feldspars in the arkosic and sub-arkosic arenites with variable, but low lithic and heavy mineral constituents. The result of the heavy mineral analysis shows dominance of non-opaque minerals (64%) compared with opaque minerals (35.08%). While the heavy mineral assemblage suggests derivation from igneous and metamorphic rocks, the presence of garnet and sillimanite point to nearness to the source. Analysis of clay-sized fraction revealed a dominance of kaolinite with illite and montmorillonite making the subordinate group within the clay minerals present. Clay species ration (high kaolinite: illite ratio) together with results from petrography suggests the possibility of warm and humid paleoclimatic conditions prevalent during deposition. From the integration of textural analysis (multivariate analysis) and observed sedimentary structures (cross-stratification, floodplain deposits, clay drapes), an agitated, fluvio-deltaic to nearshore environment of deposition is indicated by the overall sandstone geometry. This confirms the continental source for the sediments. The modal analysis further suggests a continental block provenance within a tectonic setting dominated by cratonic to recycled orogen. Such a setting is analogous to the Oban Massif for the Awi Formation and the North and Central basement complex and sediments in their second cycle of sedimentation sourced from the post-Santonian deformational episode for the Lokoja Formation.

**Keywords** Textural analysis · Heavy mineral · Modal analysis · Clay mineral · Provenance

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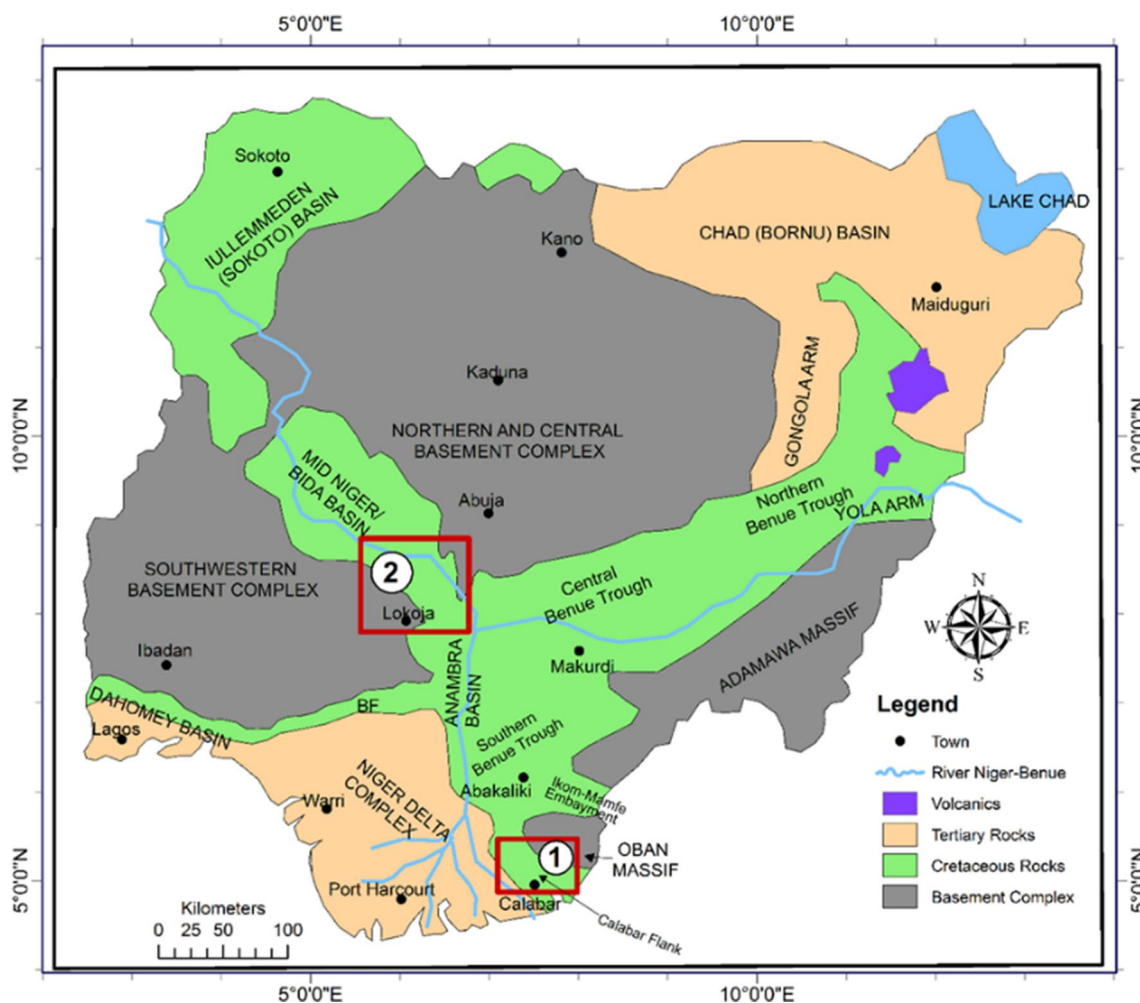
## 1 Introduction

Sedimentary rocks constitute the most abundant superficial deposits on the Earth's crust. In their nature, they retain special records and genetic significance to their past environments. The compositional framework of most detrital sedimentary rocks is a result of several factors, these include hydraulic sorting, distance from sediment source, tectonic environment, diagenesis, weathering, and transportation processes (Taylor & McLennan, 1985; Wronkiewiz and Condie 1987; Wronkiewiz and Condie 1989; Cullers et al. 1987; Eker & Korkmaz, 2011; Eker

et al. 2012; Eker & Ari, 2020). Their textures (grain sizes), composition, structures, and fossil contents give clues about their paleogeography, paleocurrent, and paleoenvironments. Many sedimentary rocks are hosts to minerals deposits and fossil fuels of great economic significance. Petroleum, natural gas, coal, salt, phosphorus, sulphur, iron, and limestone are some of the important economic products that may occur within sedimentary rocks. The Nigerian Geological domain is characterized by crystalline rocks consisting of members of the Precambrian basement complex and Jurassic younger granites, and sedimentary basins mostly of Cretaceous to Tertiary age. Although Hossain (1987) noted that the sedimentary basins are intruded in several places with rocks of basaltic compositions (dolerites dykes, gabbros, metagabbros, and in some places basaltic flows are known). In the earlier studies of the sedimentation history of southern Nigeria, Murat (1972) noted that the stratigraphic development of the southern Nigerian sedimentary basins was controlled by

sea-level changes coupled with vertical movements along horst and graben structures which underlie the basins. Of the six (6) notable sedimentary basins in Nigeria (Fig. 1), the basal units of the Calabar Flank (Awi Formation) and that of the Southern Bida Basin (Lokoja Formation) are investigated in this work. Sedimentation in the Calabar Flank and Bida Basin, which is the focus of the present contribution, occurred in the early and late Cretaceous respectively, characterizing periods of regressive cycles of deposition. Based on the categorization by age, the sandstones under study can be described as pre-Santonian and post-Santonian basal sandstones.

Many studies have been conducted and well documented by several workers on these basins (Fig. 1) and many more on-going studies are still being carried out, especially in areas of stratigraphic inconsistencies (Adeleye & Dessauvage, 1972; Adeleye & Fayose, 1978; Akande et al. 2005; Boboye & Okon, 2014; Edet & Nyong, 1993; Nyong & Ramanathan, 1985; Ojo & Akande, 2003; Okon et al. 2017;



**Fig. 1** Geological sketch map of Nigeria showing the location of the Calabar Flank (1) and the Bida Basin (2) where the study was carried out (geological outline adapted from Obaje et al. 2004)

Petters et al. 1995, 2010; Rahaman et al. 2019, 2020; Zabor-ski, 1998).

In this study, the classical sedimentological concept involving analysis of ogives of several line segments symbolising distinct sub-populations moved by different transportation means has been adopted. Typically, as earlier noted by Visher (1969), fluvial sediments are characterized by three-line segments with the mid-segment representing the saltation fraction, the lower segment representing sediments transported by traction (rolling) and the upper segment representing sediments transported by suspension (fines). The presence/absence of any of these sub-populations in a fluvial regime may be suggestive of some hydrodynamic implications (Opreanu, et al. 2007). The general objective of this contribution is to present the sedimentological features of the pre-Santonian and post-Santonian basal sandstones of the Calabar Flank and Bida basin respectively based on field mapping, textural analysis, mineralogical of clay-sized particles, and petrographic findings. These are integrated to enable the characterization of provenance, paleo-depositional conditions, and paleogeographic implications.

## 2 Geologic settings and study area description

The Calabar Flank and the Bida Basins are sub-basins of the Benue Trough. In addition to both basins, the Anambra basin and Ikom-Mamfe Basin extending out of its main axis also make up the Southern Benue Trough domain (Nwajide, 2013). Across the entire landmass of Nigeria, Cretaceous strata covering about one-fourth of the landmass are observed to form sedimentary basins with the Benue Trough being the most extensive. The Benue Trough defines an aulacogen that runs from underneath the Niger Delta in the south to the northeastern part of Nigeria where the Bornu (Chad) basin is noted to overlie the basin. It has been the focus of intense research since the early 1950s. King (1950) attributed its origin to the extension of the Atlantic rifts onto the African plate as Cretaceous rift valleys. This contribution was followed by intensive research performed by Reymont (1965), Adeleye and Dessauvage (1972), Murat (1972), Dessauvage (1975), Whiteman (1982), Zabor-ski (1998) and Petters et al. (2010). Their contributions shed light on the origin, evolution, tectonics, stratigraphic development, and magmatism associated with the Benue Trough and adjoining sub-basins. Its study is pivotal to the understanding of the geological characteristics of this study, as it separates the Bida Basin to its left and Calabar Flank to its right (Fig. 2). The regional strike of the Calabar Flank and Bida basin is similar and oriented to the NW–SE trend. Therefore, the basal sediments of the Calabar flank and Bida basin are

compared within certain frameworks of similarities and differences (Table 1).

Figure 2 Geological map of Calabar Flank (Southern map) and Bida basin (Northern map). (modified after Okon et al. 2017; Rahaman et al. 2019).

The basin evolution of the Calabar Flank is related to the separation of African and South America continental plates coupled with the eustatic changes in the sea level, hence suggesting a rift origin as had been defined by many workers. Petters (1980) related the Calabar Flank to other south Atlantic Cretaceous marginal basins with similar horst and graben structures. Nyong and Ramanathan (1985) suggested that the basement structures (horst and graben) and eustatic sea-level changes controlled the Mid-Cretaceous sedimentation in the basin. The structural settings and eustatic modulations gave rise to a stratigraphic evolution with coarse-pebbly, continental sandstones of the Awi Formation marking its basal unit. The deposition of the continental sandstone was followed by a complete marine succession. The succession includes the shallow marine Albian Mfamosing Limestone, Cenomanian–Turonian Ekenkpon Shale, Coniacian New Netim Marl, and the late Campanian–Maastrichtian Nkporo Shale, all within the Calabar Flank (see Fig. 2). There has been argument of more than one deformational episode affecting the sediments of the Calabar Flank but that of the Santonian events is observed to have stood out. The Santonian event affected sediments of the Southern and Central Benue Trough and the compressional tectonics that developed into the Abakaliki anticlinorium shifted the depocenter of the southern Benue basin to the west and east (Anambra basin and Afikpo syncline). This development redirected the paleo-sea responsible for the deposition of marine clastics in the southern section (Calabar Flank) and continental (alluvial) clastics in the Bida basin.

On the origin of the Bida basin, a rift model was proposed due to the presence of irregular basin floor, axial positive anomaly flanked by negative anomalies (Nwajide, 2013; Ojo & Ajakaiye, 1989). This notwithstanding, Nwajide (2013) also observed that the basin width to length ratio, absence of volcanic and /or igneous intrusive rocks, faulting and evidence of intermittent uplifts places do not strongly support the rift-origin of the basin. Braide (1992) suggested a ramp-thrust complex, from the geophysical investigation, stressing that extensional tectonics played a significant role in its evolution. The lineament trend of the Bida basin and the Calabar Flank are somewhat coincident averaging around 107° and 163° respectively. These lineament trends are not infrequent in Africa and have notably been reactivated during most of the post-Santonian times. The Lokoja Formation (Campanian) unconformably overlies the crystalline basement complex consisting of continental fluvial sediments following the subsidence of the Bida basin.

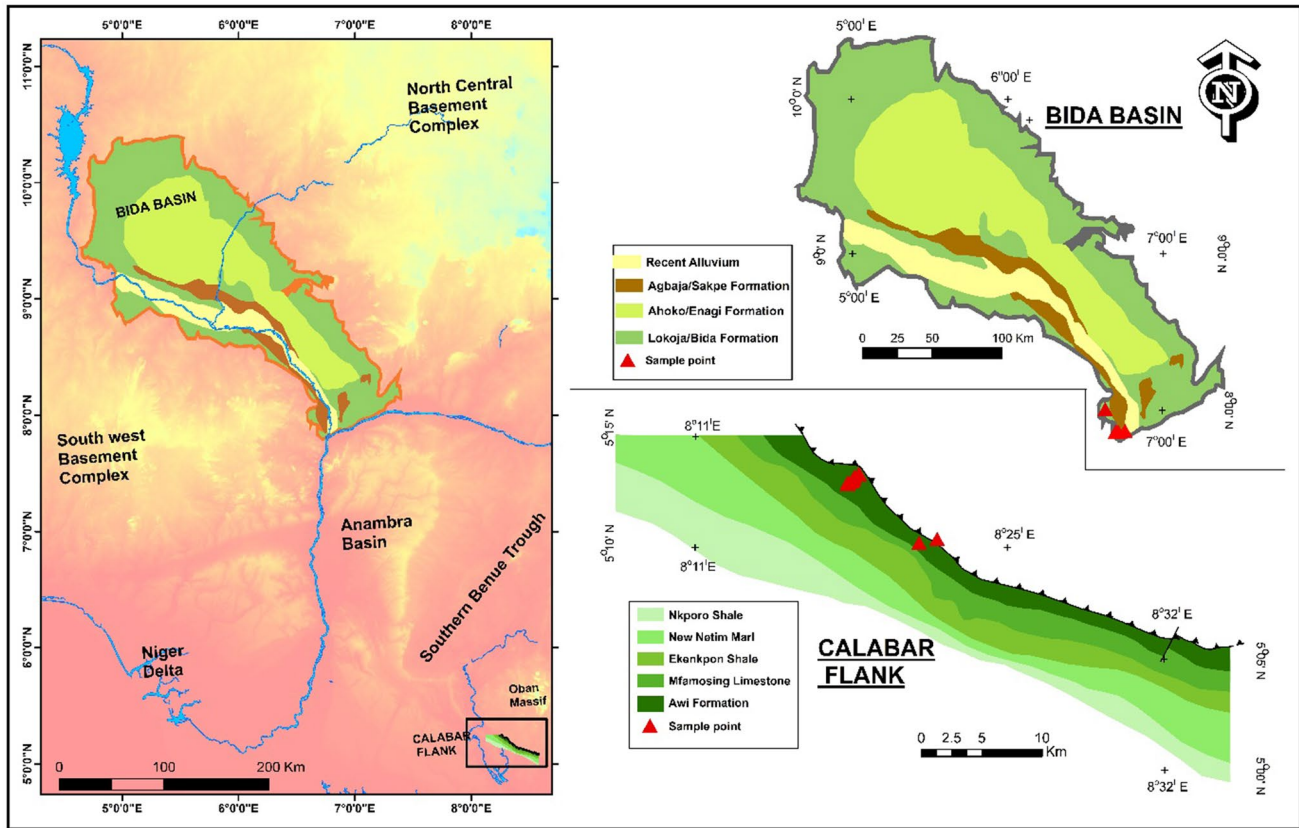


Fig. 2 Geological map of Calabar Flank (Southern map) and Bida basin (Northern map) (modified after Okon 2017, Rahaman et al. 2019)

Table 1 Geological features (similarities/contrast) of the Calabar Flank and Bida basin

Feature	Calabar Flank	Bida Basin
Origin	Related to the basin forming processes of the Benue Trough	Related to the basin development processes of the Benue Trough
Orientation	NW–SE regional strike	NW–SE regional strike
Age	Pre-Santonian (Neocomian)	Post-Santonian (Campanian)
Formation	Awi formation	Lokoja formation
Lithology	Fluvio-deltaic?? sediments	Fluvial sediments

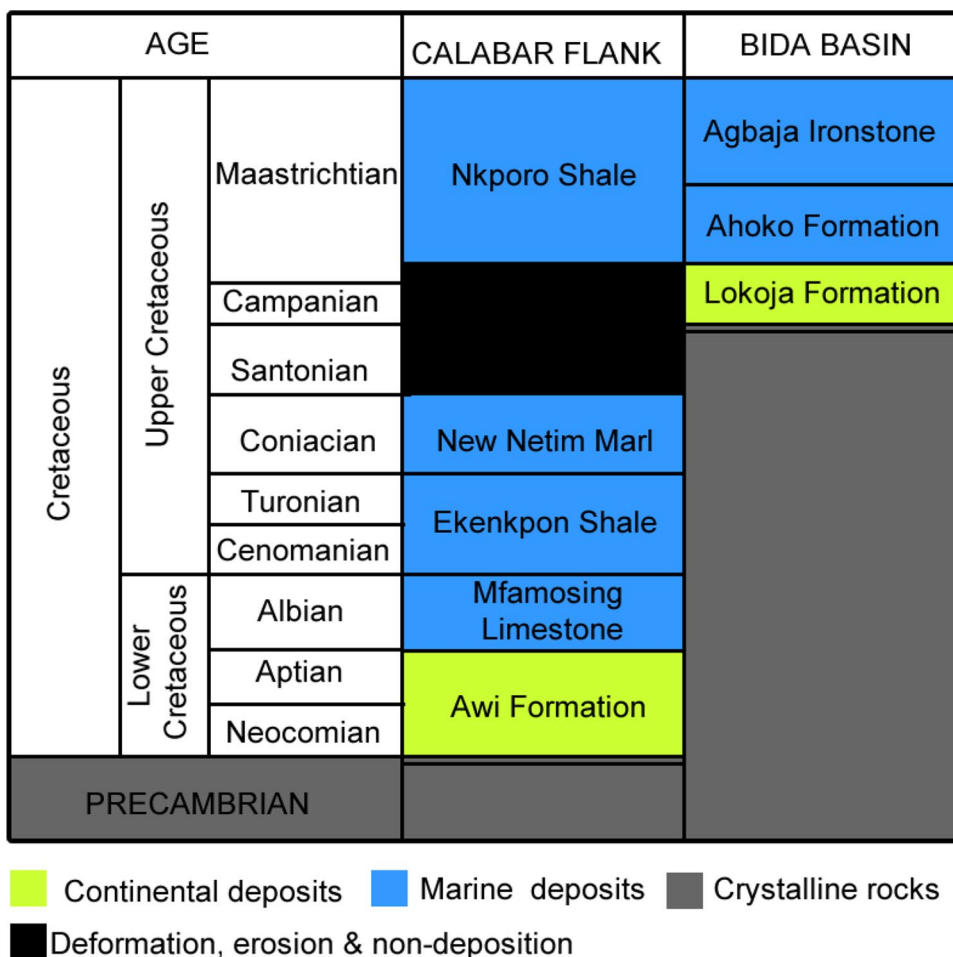
It is overlain in the southern Bida basin by Ahoko (Patti) Formation. Agbaja Formation stratigraphically overlies the Ahoko Formation and it is composed of ironstone (Fig. 3). The sedimentological characteristics of the Awi Formation (Neocomian–Aptian) and the Lokoja Formation (Campanian–Maastrichtian) are considered for provenance and paleo-depositional conditions. The Lokoja Formation, the basal unit of the Southern Bida Basin with its lateral equivalent in the Northern section of the basin, the Bida sandstone are of continental origin.

### 2.1 Study area description

This study covers the basal section of the Calabar Flank, the Awi Formation, exposed in south-eastern Nigeria, precisely north of Calabar metropolis. It unconformably overlies the Precambrian Basement rocks of the Oban Massif (see Fig. 2). Also, the Lokoja Formation is located along the Lokoja-Abuja highway (see Fig. 2), north-central Nigeria.



**Fig. 3** Stratigraphic position and age of the Awi Formation and Lokoja Formation (after Okon et al. 2017; Petters et al. 2010; Rahaman et al 2019)

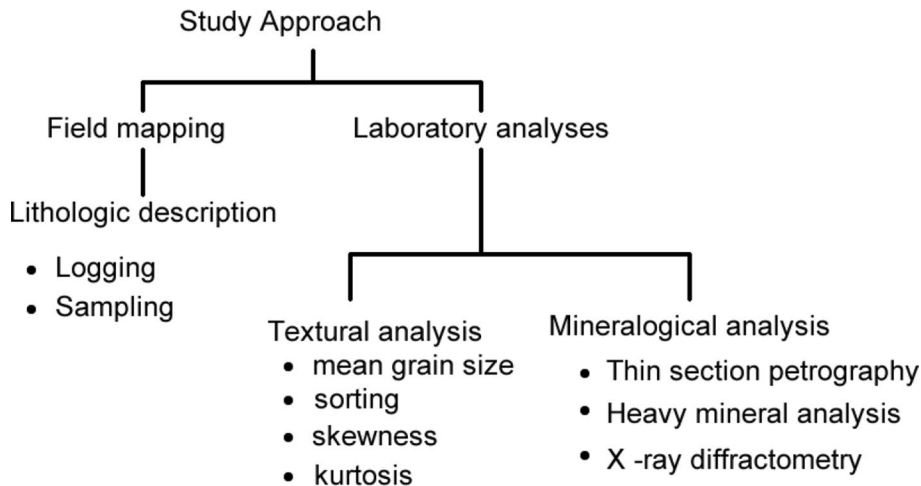


### 3 Materials and methods

The approach used in this study includes field studies and laboratory analyses (Fig. 4). The field study includes detailed mapping and description of nine (9) outcrops in exposed sections of the formations (Awi Formation and

Lokoja Formation) respectively. Collected samples were forty-nine (49) in number. Field procedures involved measurement of bed thickness and description of lithology description, strike, and dip of bedding planes. During the field investigation, sedimentary structures comprising ripples, parting lineation and sole marks, stratification

**Fig. 4** Flow chart showing the methodological approach



(hummocky, flaser, laminations, planar, trough, herringbone), bed grading types were noted. Sketches and photographs were taken and lithology logs of the outcrops were documented (see supplementary material for this article), however, two composite lithology logs describing the facies succession is presented.

Standard laboratory procedures were adopted for the grain-size analysis (40 samples), thin section petrography (20 samples), heavy mineral analysis (18 samples) and mineralogy of clay-sized particles (6 samples) was carried out to characterize the textural characteristics and mineralogy of the sandstones. Sieve analysis for unconsolidated sand-size samples was carried out after each sample was coned and quartered using an otto-type sample splitter. This was done to homogenize the samples and reduce bias to the barest minimum. For each sample prepared, 100 g was weighed out using a weight balance and emptied onto the top of a set of sieves stacked from coarsest (2000 microns) at the top to the finest (< 63 microns) below ranging across the sand size classification of (0Φ) to (4.0Φ). This analysis was carried out using an Endecott sieve shaker for a constant time (duration: 20 min, amplitude: 10 and motion: continuous). After sieving, the weight retained in each sieve and the pan was recorded (additional information and tables are in the supplementary materials). The cumulative weight percentages were determined and tabulated. The data generated were subjected to statistical analyses in line with the formula presented by Folk and Ward (1957), Friedman (1961) and Opreanu et al. (2007) and interpreted based on the recommended descriptive classification. It is well known that grain size parameters facilitates the unravelling of complicated processes involved in sedimentation and thereby gathering intrinsic information about their depositional environment; among such properties include sediment source, energy flux, nature of the transporting medium, and geometry of the depositional basin. Success has been recorded in distinction between beach, dune, and river sediments by earlier workers (Mason & Folk, 1958, Friedman, 1967; Visser, 1969; Nordstrom, 1977; Ganesh et al. 2013; Vakalas et al. 2004; Fadiya, 2015; Kermani et al. 2015; Essien et al. 2016; Ocheli et al. 2018) using grain size data. It is important to note that besides the original size of materials available at the source area and the environmental energy (current velocities) of the grains, other processes (broken molluscan shell fragments and activities of bioeroding organisms) introduce fines into the size fraction available for deposition and if not properly accounted for, may grossly alter the overall interpretation of the size characteristics. All these were considered during the interpretation of the results of textural analysis. Multivariate analysis of mean, sorting, skewness and kurtosis further eliminates the limitation regarding overlaps in textural analysis interpretation using univariate and bivariate analyses. Sahu (1964) buttressed the significance

of utilizing the multivariate analysis to constrain the environmental interpretation using textural parameters due to within-sample variation observed in a population. Discrimination analysis is hinged on the depositional mechanisms and as noted by Sahu (1964), it may be difficult to use it to discriminate against an aeolian dune and aeolian flat environments, but clear distinctions are observed between the latter and river or beach sands. The following Eqs. 1–3 were erected (the values from the calculated parameters are in the supplementary materials of this paper).

$$Y1 = (Y_{\text{aeol:beach}}) = -3.5688 Mz + 3.7016\sigma_I^2 - 2.0766Sk_I + 3.1135K_G, \quad (1)$$

$$Y2 = (Y_{\text{beach:Sh.marine}}) = 15.6534 Mz + 65.7091\sigma_I^2 + 18.1071Sk_I + 18.5043K_G, \quad (2)$$

$$Y3 = (Y_{\text{Sh.marine:fluvial}}) = 0.2852 Mz - 8.7604\sigma_I^2 - 4.8932Sk_I + 0.0482 K_G. \quad (3)$$

In this study, the linear discrimination equation for Eqs. 2 and 3 which relates directly to statistical characteristics of the samples, were plotted together to further strengthen the overarching influence of fluvial (high energy) processes through multivariate discriminant analysis.

The thin section slides were prepared using GTSI thin section cut-off saw while the heavy mineral concentrates were mounted on glass slides after gravity separation of mineral grains greater than 2.85 g/cc (the specific gravity of bromoform) from lighter ones for samples collected during field investigation. The prepared thin sections and separated heavy minerals were analysed under the petrographic microscope. Following the Gazzi-Dickinson method, point counting was completed and minerals present were tabulated. The analysis was carried out in the Department of Geology, University of Ibadan, Nigeria. These minerals are present in the parent rocks as either rock-forming minerals or as accessory minerals, such as quartz, feldspar, mica, rock fragments, and for heavies, zircon, staurolite, rutile, garnet, and tourmaline (Mange & Maurer, 1992). The proportion of stable heavies in the association (e.g., zircon, rutile and tourmaline), when plotted on a ternary diagram gives an index referred to as ZTR index (Hubbert, 1962), which basically is used to characterize the degree of mineralogical maturity of the grains. This mineralogical index (ZTR index), was determined using the relation:

$$\text{ZTR Index} = \text{Zircon} + \text{Tourmaline} + \text{Rutile} / \Sigma \text{non-opaque} \times 100.$$

X-ray diffraction (XRD) analysis was carried out on some clay fractions to identify the dominant minerals in

the samples using Empyrean diffractometer. The analysis was carried out via the reflection-transmission spinner stage using the Theta-Theta settings. Two-Theta starting position was 0.00483 and ends at 75.000 with a two-theta step of 0.026 at 3.57 s per step. Tube current was 40 mA and the tension was 45VA. Fixed Divergent Slit size of 1° was used and the goniometer radius was 240 mm. The  $2\lambda$  position of the diffraction peak was measured as the centre of the peak at 80% peak height. This analysis was carried out at the Nigerian Geological Survey Research Laboratory (NGSRL), Kaduna, Nigeria.

X-ray diffraction (XRD) analysis was carried out on some clay-sized fractions (< 63 microns) to identify the dominant minerals in the samples using Empyrean diffractometer. The analysis was carried out via the reflection-transmission spinner stage using the Theta-Theta settings. Two-Theta starting position was 0.00483 and ends at 75.000 with a two-theta step of 0.026 at 3.57 s per step. Tube current was 40 mA and the tension was 45VA. Fixed Divergent Slit size of 1° was used and the goniometer radius was 240 mm. The  $2\lambda$  position of the diffraction peak was measured as the centre of the peak at 80% peak height. This analysis was carried out at the Nigerian Geological Survey Research Laboratory (NGSRL), Kaduna, Nigeria.

## 4 Results and discussions

### 4.1 Field observations

Field investigation carried both in the Calabar Flank (Awi Formation) and Bida Basin (Lokoja Formation) revealed that these sediments belong to the basal units of the two basins. Although not the entire thickness is exposed for outcrop examination in most cases, there were clear cases of sediment-basement contacts. In the Awi Formation, Unconformably overlying the basement at its contact was a thick conglomerate unit that consists of angular pebbles with an overall fining upward succession (Fig. 5a). Several visited outcrops revealed the presence of pebble beds; their clasts are subangular to subrounded, and their size ranges from 10 to 80 mm (Fig. 5b), medium-coarse grain, planar cross-bedded sandstones (Fig. 5c), shale/mudstone units that were characterized by crudely developed flaser beddings (Fig. 5d) and a 30 cm lignite band. Point bar deposits overlain by bluish-grey shaley units was observed in the Awi Formation exposed along Njagachang area with the sandstone units characterized by normal grading, planar / trough cross-bedding, herringbone cross-beds towards the top of the unit.

Although earlier studies (Nton, 1999, Boboye and Okon 2014, Okon, 2015) had accounted for a fluvial (meandering

environment of deposition) based on the relationship between the medium-coarse grain sandstone underlying the flood-plain muds and lignite bands, there is compelling evidence to include typical alluvial fan deposits to the more proximal facies in the formation (see Fig. 5). Of significant note in the Awi Formation is an indurated ferruginized layer that is conglomeratic towards the base. This unit (0.4 m thick) shows a fining upwards succession, with a profile from granule-size to mud-clast size range (paleosol). This unit (paleosol) was interpreted by Okon (2015) as a period of break-in sedimentation during deposition of the Awi formation while active sedimentation returned in the basin with another cycle of alluviation. The top of the Awi Formation in the Calabar Flank marks the first record of marine incursion into the southern Nigeria sedimentary basins with the deposition of shallow marine Mfamosing Limestone.

In the Bida Basin, Lokoja Formation also mapped extensively along the Abuja-Lokoja highway revealed the presence of a similar sedimentary unit that is typical of alluvial fan settings although no paleosol was mapped here. Generally, it consists of a fining upward succession comprising of conglomerates (and boulders) at the base, succeeded by coarse-grain sandstone and mudstones/claystone interbeds. It is characterized by light grey-brown, poorly sorted—moderately sorted, planar cross-bedded, medium to coarse grain (angular grains) sandstones deposited during the Campanian epoch. There is a clear indication of sediment – basement rock contact exposure beside crusher dumpsite, along Lokoja-Abuja road (Fig. 6a, b). A summary of the facies characteristics for the Awi Formation and Lokoja Formation is presented in Table 2.

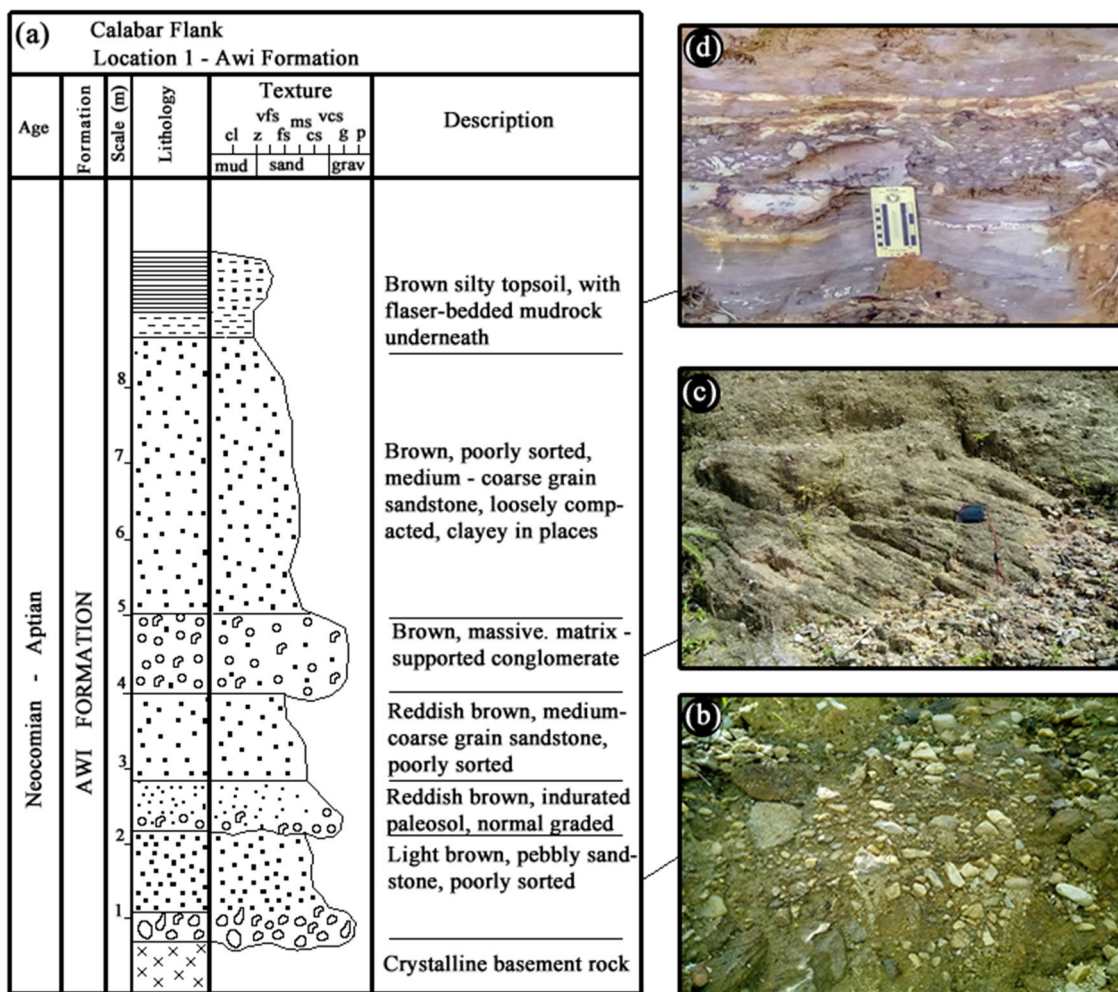
### 4.2 Textural parameters

A detailed description of the textural parameter in terms of univariate analysis, bivariate plots and multivariate analysis for the sediments of Awi Formation and Lokoja Formation have been presented and data are analysed.

#### 4.2.1 Univariate analysis

The summary of the results of grain size analysis is presented in Table 3 (detail description of the analytical result is contained in the supplementary data). The description of the statistical parameters used for characterizing the size fraction as they suggest depositional processes and dynamics is referred to as univariate analysis.

In this analysis, the significance of individual statistical measures such as mean, sorting, skewness and kurtosis are discussed. Friedman (1967) noted that despite the fact that these measures characterized the depositional environmental conditions they are not without overlap between different



**Fig. 5** **a** Composite lithologic section for Location 1, Awi Formation; **b** photograph showing angular to sub-rounded pebbly sandstone that overlies the basement; **c** large scale tabular cross beds overlain

by massive conglomeratic sandstone; **d** Bluish—grey to brown flaser bedded mudrocks

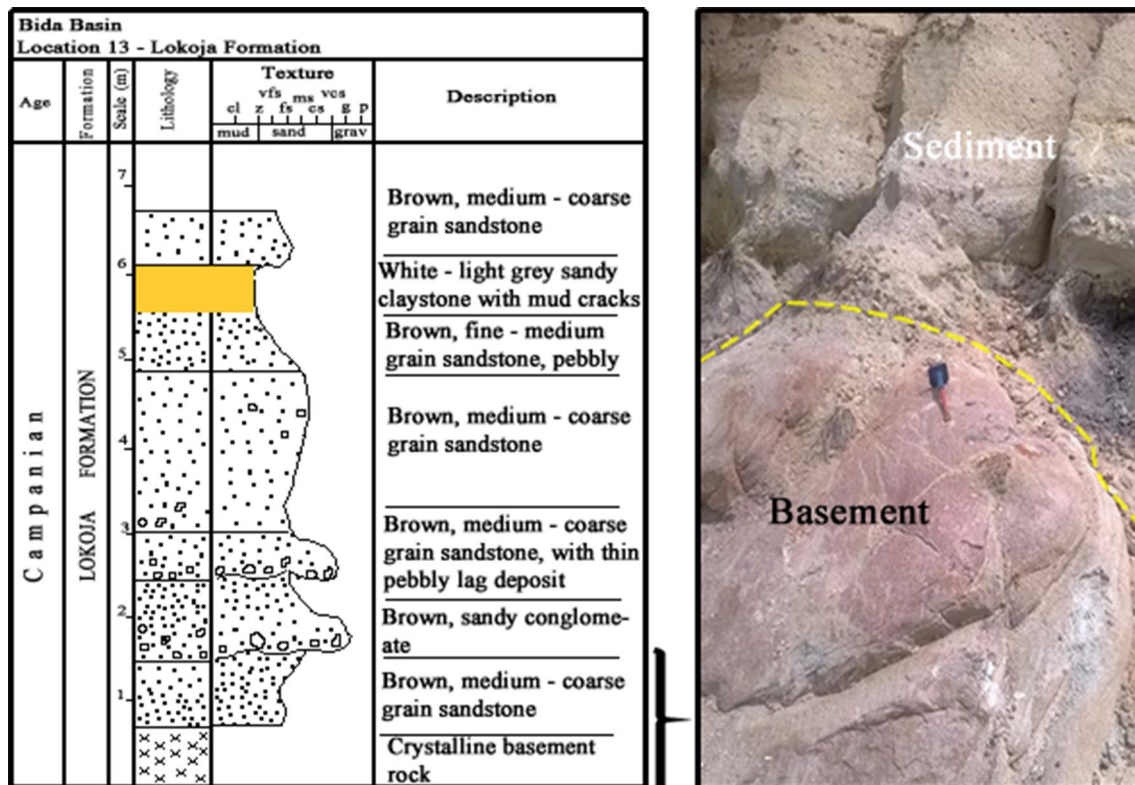
environment. For instance, mean grain size and sorting have been used independently to characterized and differentiate between beach and river sands. Such grain size parameters are very useful in environmental interpretation especially when they are integrated with other parameters such as sedimentary structures and geological settings.

**Mean size ( $M_z$ )** The graphic mean size, which is an index of energy conditions, refers to the average size of the sediments represented in phi ( $\phi$ ) units (Essien et al. 2016). It implies the average kinetic energy (velocity) of the depositing agent. In this study, Awi Formation is characterized by fine-grained sands ( $3.76 \phi$ ) to very coarse grain ( $-1.01 \phi$ ) sands that is pebbly in places. The Lokoja Formation is also characterized by mean grain size ranging from medium grain sands ( $1.20 \phi$ ) to coarse grain sands ( $0.49 \phi$ ). This notwithstanding, Okon and Essien (2015) noted that the sediment sizes at the provenance could also affect the representation

of whatever size fraction is available for transportation. Therefore, this parameter is to be interpreted with some caution. This basically suggests that there is dominance of medium-coarse grain sand (MS) size sediments indicating deposition in moderate—turbulent energy conditions. Typically, as expected in alluvial deposition, there is attendant flooding and intermix of coarse material. Within the floodplain and meandering setting, finer clasts accumulate at the expense of coarser clasts due to waning energy of deposition.

**Inclusive graphic standard deviation ( $\sigma_1$ )** The inclusive standard deviation is a measure of the coefficient of uniformity of the grain-size distribution (sorting). It accounts for fluctuations in the hydrodynamic energy conditions of the depositional environment (Sahu, 1964). Sorting exhibits an inverse relation with Standard deviation. Sorting values range in Awi Formation, from  $0.58 \phi$





**Fig. 6** a Composite lithologic description of Lokoja Formation exposed along Abuja-Lokoja highway showing sediment-basement contact (yellow dashed line)

**Table 2** Summary of facies characteristics in the Awi formation and Lokoja formation

Formation	Depositional setting and facies characteristics			
	Alluvial fans	Point bar	Flood plains	Back swamp
<b>AWI formation</b>				
Descriptions	Pebbly sandstone with characteristic lag deposit towards the base	Medium to coarse grain sandstones, planar—cross bedded, exhibit fining upwards succession	Mud-supported sandstone, with mud-drapes along the cross beddings, mudstones, plain beds and gently dipping	Lignite deposit, underlain by flaser-lenticular bedded siltstones and overlain by fragmented paleosol in places
Fossils	Nil	Nil	Nil	Nil
Energy model	High energy	Intermediate energy	Low energy	Very low energy
<b>Lokoja formation</b>				
Descriptions	Boulder—Pebbly sandstone with characteristic lag deposit towards the base	Medium to coarse grain sandstones, cross-bedded, exhibit fining upwards succession	White claystones and mudstones, plain beds and gently dipping beds in places	Nil
Fossils	Nil	Nil	Nil	
Energy model	Very high energy	Intermediate	Low energy	

to 1.80  $\phi$  and in Lokoja Formation from 0.58  $\phi$  to 1.92  $\phi$ . This indicates that both formations have in general poorly sorted sediments. They have minor moderately sorted sands. The variation of sorting across the samples is an indication of continuous input of end-member textural

classes (fines/coarser materials) during deposition (Baiyegunhi et al. 2017; Essien & Okon, 2016; Ganesh et al. 2013; Inyang et al. 2014). Due to the position of the Lokoja formation, it is unlikely that re-deposited well-sorted beach materials could account for the moderately

**Table 3** Summary of the statistical parameters and their interpretation

	Mean			Sorting			Skewness			Kurtosis		
	Min	max	Av	Min	Max	Av	Min	Max	Av	Min	Max	Av
Awi formation ( $n=23$ )	-1.01	3.76	1.44	0.58	1.80	1.19	-0.19	0.77	0.16	0.65	1.52	1.15
Interpretation	VCS	FS	MS	MWS	PS	PS	CSK	VFSK	FSK	VPK	VLK	LK
Lokoja formation ( $n=17$ )	0.49	1.20	1.20	0.58	1.92	1.08	-0.28	1.00	0.24	0.53	1.61	1.09
Interpretation	CS	MS	MS	MWS	PS	PS	CSK	VFSK	FSK	VPK	VLK	MK

VCS very coarse sand, CS coarse sand, MS medium sand, FS fine sand, PS poorly sorted, MWS moderately well sorted, CSK coarse skewness, VFSK very fine skewness, FSK fine skewness, VPK very platykurtic, LK leptokurtic, VLK very Leptokurtic, MK mesokurtic

well sorting of sediments encountered. As noted by Friedman (1962) depending on the grain size and the prevailing condition, fluvial sands may be represented in the well sorted class. The addition of freshly weathered materials accounts for the predominant poorly sorted nature of sediments from both formations (Angusamy & Rajamanickam, 2006; Okon, 2015; Rajesh et al. 2007; Ramanathan et al. 2009).

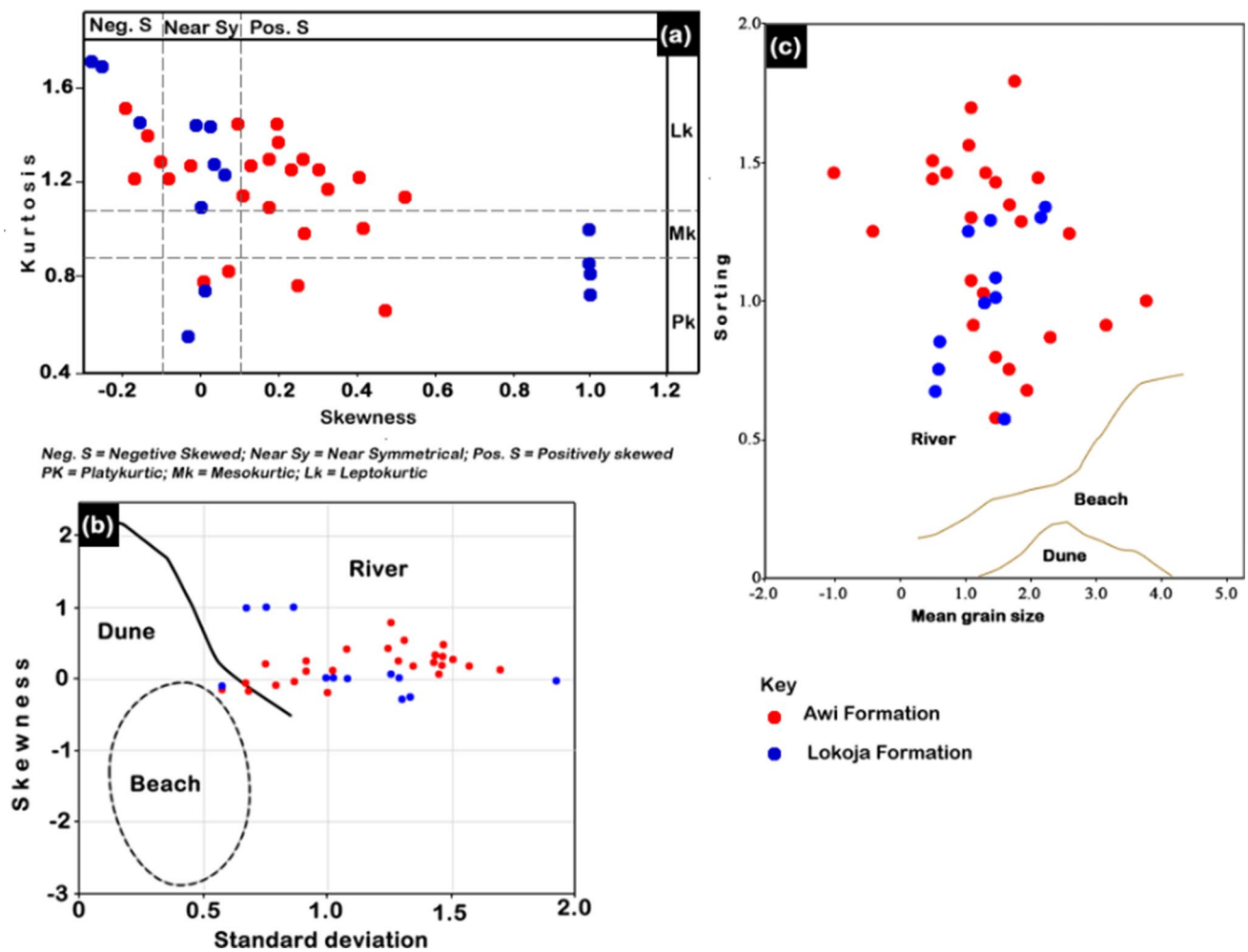
**Skewness ( $S_G$ )** The graphic skewness is a measure of the symmetrical distribution of grain-size parameter that reflects spread characteristics in the tails of the curve. An asymmetrical curve with excess fine particles has a fine-size tail and displays a positive phi ( $\phi$ ) value, while sediments with excess coarse material show negative phi ( $\phi$ ) values. A zero phi ( $\phi$ ) value is indicated by a symmetrical curve. Inclusive graphic skewness for the Awi Formation ranges from  $-0.19 \phi$  to  $0.77 \phi$  (coarse skewness to very fine skewed), with an average of fine skewness ( $0.16 \phi$ ). The Lokoja Formation also showed similar skewness characteristics like the Awi Formation with a range from coarse skewness to very fine skewness ( $-0.28 \phi$  to  $1.00 \phi$ ), with an average of  $0.24 \phi$  (fine skewness). The majority of the samples are finely skewed (positive skewness) reflecting fluvial characteristics with the influx of materials of all sized during deposition. While studying recent sediments, Rajasekhara Reddy et al. (2008) noticed that sediments with positive skewness were sampled from sheltered low energy (riverine) environments, whereas negatively skewed sediments characterize deposition in high energy (beach/swash zone) environments. By analogy, therefore, the Awi Formation and the Lokoja Formation may likely have been deposited by fluvial processes.

**Kurtosis ( $K_G$ )** The graphic kurtosis values for the Awi Formation sandstone ranges from  $0.65 \phi$  to  $1.52 \phi$  and average value is  $1.15 \phi$ , hence they are very platykurtic to very leptokurtic. For Lokoja Formation, values range from  $0.53 \phi$  to  $1.61 \phi$  (average of  $1.09 \phi$ ) suggesting leptokurtic – mesokurtic sands. Since the graphic kurtosis quantitatively measures how sediments depart from normality. Such deviation according to Friedman (1962) is

an environmental sensitive parameter. It clearly describes the sorting at the tails of the curve relating them to the central portion.

#### 4.2.2 Bivariate and multivariate analysis

Sedimentologists have noticed that sand and sandstones represent complex mixtures of modes and as such overlaps must be found to persist in characterizing environments. Over the past decades, several approaches have been used to solve problems related to this, Friedman (1967) pointed out the significance of using bivariate analysis to differentiate depositional environments despite the opinion of Gees (1965) to the contrary. The use of scatter graphs (bivariate plots) of some statistically determined grain size parameters to distinguish between different depositional settings assumes that these statistical parameters reflect differences in the mechanisms of sediment transportation and deposition became famous (Boboye & Okon, 2014; Friedman, 1961; Martins, 2003; Sutherland & Lee, 1994). They noticed that the sharp distinction between the beach and fluvial sands is hinged upon the processes operating during the deposition of the sands. Of course, overlaps between environments may not be completely ruled out, certain properties of the sediments (sedimentary structures, fossil content, etc.) could be integrated into the analysis to tell apart sediments deposited by similar processes but different environment (Adamu et al. 2020; Essien & Okon, 2016, 2019). In this study, the sediments of Awi Formation and Lokoja Formation were plotted to determine the depositional environment using kurtosis vs skewness, skewness vs standard deviation (sorting) and sorting vs mean grain size. As observed in this study, the plot of skewness against kurtosis showed a significant population of the sandstone of Lokoja Formation being negatively skewed with a majority of those of the Awi Formation ranging from near symmetrical to positively skewed sands (Fig. 7a). The behaviour of the Lokoja sands can be interpreted as sediments in their second cycle of sedimentation mixed with those from weathering of fresh basement. To further clarify this position, inclusive graphic skewness was plotted against



**Fig. 7** Bivariate scatter plot of **a** mean versus sorting for Awi Formation and Lokoja Formation, **b** Skewness against standard deviation (sorting) for Awi and Lokoja Formations (Fields after Martins, 2003)

standard deviation (sorting), using the fields from Friedman (1961) as a discriminator, it was observed that 95% of the samples plotted within the field of fluvial mechanism of transportation and deposition (Fig. 7b).

For further clarification, since both mean grain size and sorting are hydraulically controlled, the plot of sorting against mean grain size becomes a powerful tool for interpreting the genesis of sediment; this plot clearly distinguished the sediments as deposited through fluvial processes (Fig. 7c). The multiplicity of modes may result in a distribution that are not characteristic of the environment and therefore when characterizing size distribution of sands, the depositional conditions interpreted from sedimentary structures and/or fossil contents may help constrain the assertions made during analysis of textural parameters.

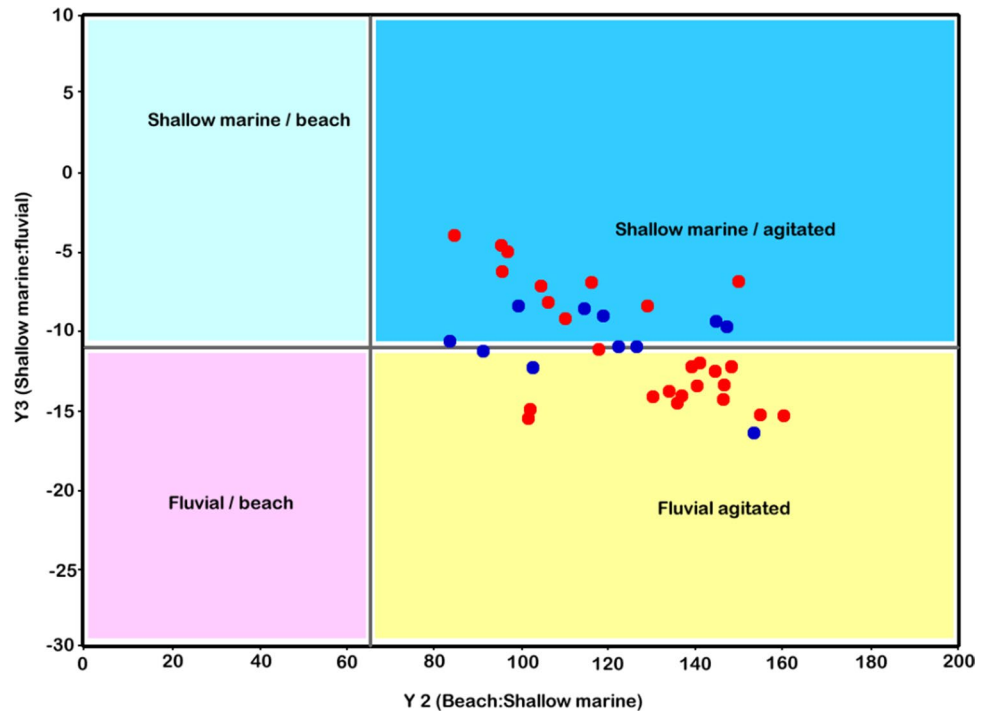
The linear discriminant function for beach/shallow marine and shallow marine/fluvial environmental settings (Fig. 8) and the samples plotted in the fluvial fields.

### 4.3 Mineralogical analysis

#### 4.3.1 Mineral compositions and classification

The result of the petrographic analysis is summarized in Table 4. The table presents a summary of the recalculated abundances of detrital mineralogy in the studied sandstones (Awi sandstone and Lokoja sandstones). From this study, it is clear that the Awi Formation and Lokoja Formation are composed of angular fragments suggesting a short transport distance from the source. Quartz

**Fig. 8** Relationship between the discriminate functions Y2 and Y3 showing the estimated environments



**Table 4** Result of petrography and recalculated abundances of quartz, feldspar and rock fragment

Sample no	Qtz	Fsp	Msc	Bio	Rkf	HM	others	Qtz (%)	Fsp (%)	Rkf (%)
Awi/L1/a	62	14	6	7	6	7	–	67.74	22.58	9.68
Awi/L1/b	43	22	6	3	2	10	12	60.08	28.65	11.27
Awi/L1-c	76	45	17	3	1	7	8	55.00	32.78	12.22
Awi/L1-d	62	34	13	2	5	–	14	56.88	31.19	11.93
Awi/L2-b	60	35	17	13	17	3	8	54.00	31.00	15.00
Awi/L4-a	58	28	15	8	4	4	12	58.00	28.14	13.36
LKL1	83	12	4	6	3	2	–	83.00	12.00	3.00
LKB4	81	13	9	2	4	–	–	81.00	13.00	4.00
LKP2	83	10	4	3	1	1	4	83.00	10.00	4.00
LK74	80	13	3	2	1	–	3	80.00	13.00	3.00
LKP3B4	82	10	–	4	5	1	1	82.00	10.00	5.00
LKP4	83	13	5	5	2	2	4	83.00	13.00	2.00
Ag/L2-a	76	18	9	7	8	20	10	73.79	17.48	8.73
Ag/L4-c	76	18	6	–	2	4	13	76.00	18.00	6.00
Pal/B4-a	94	14	8	3	18	3	8	81.04	12.07	6.89
Pal/B4-b	93	20	12	3	15	–	5	74.40	16.00	9.60
Pal/B5-a	71	16	10	–	7	5	–	77.17	17.39	10.87
Pal/B5-b	74	22	89	–	3	4	10	71.84	20.39	6.79
Pal/B5-c	82	16	16	–	8	4	–	71.68	12.93	15.39

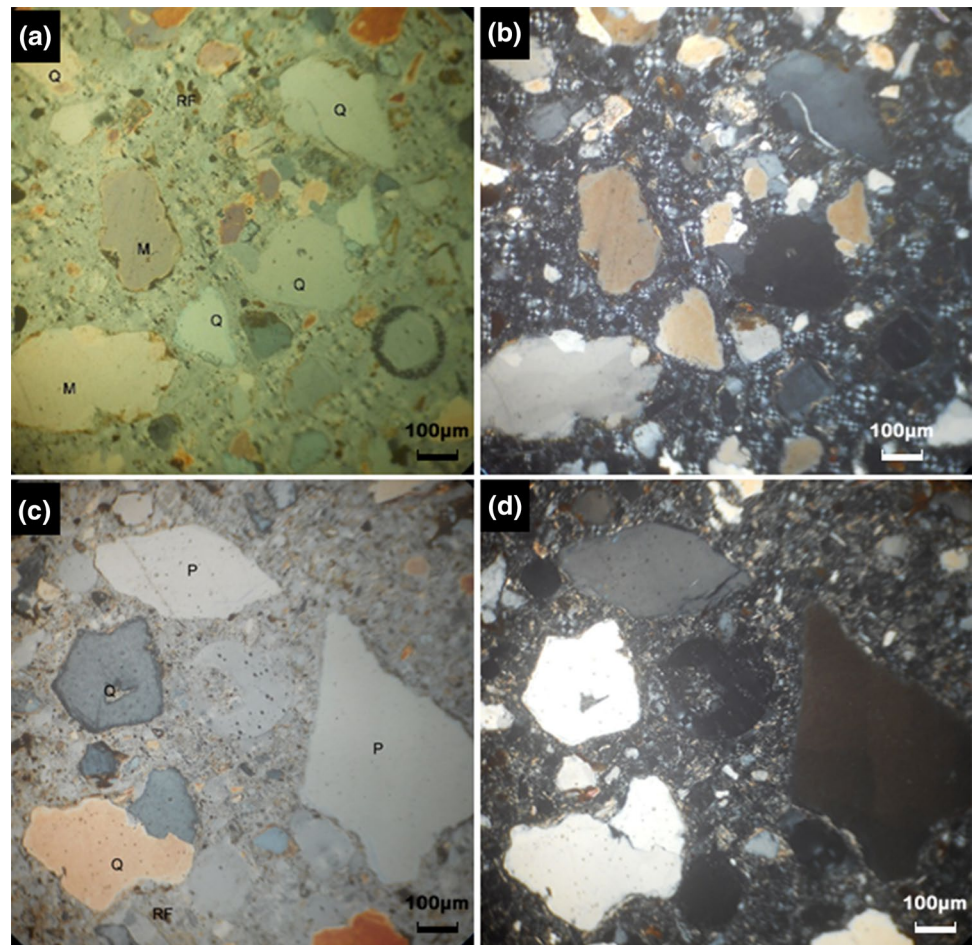
Qtz quartz, Fsp feldspar, Msc muscovite, Bio biotite, Rkf rock fragment, HM heavy minerals

(monocrystalline and polycrystalline) were identified, followed by feldspars, most of which had weathered to clayey matrix within which the grains float, rock fragments, mica, and heavy minerals, all making up the detrital constituents (Figs. 9, 10). The percent ratio of the quartz-feldspar-rock fragment was computed and used for sediment

classification (Fig. 11a), paleoclimate (Fig. 11b) and tectonic setting interpretation (Fig. 11c, d). It is noteworthy that a short distance of travel is a control on the form and composition of the sandstone at the time of deposition. The energy of the depositing medium and processes of mechanical breakdown and/or abrasion, accounts for the



**Fig. 9** Photomicrograph showing framework grains of **a, b** sandstones of Awi Formation floating in argillaceous matrix and siliceous cement, **c, d** illustration of angular and poorly sorted nature of the grains in the sandstones



poor sorting with clasts of different sizes held together in a fine (clay/silt) matrix.

#### 4.3.2 Palaeotectonic and palaeoclimatic setting

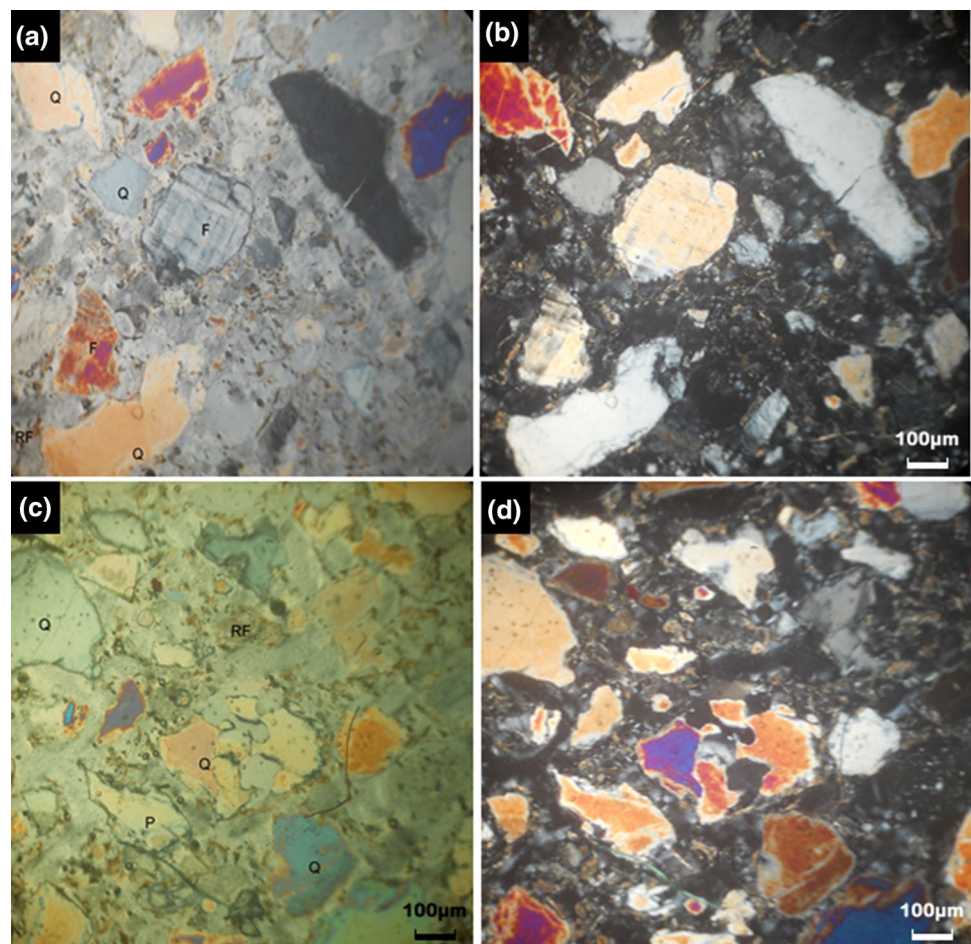
There is an overwhelming concentration of quartz in the Lokoja sandstones compared to the Awi Formation and based on this, the sandstones are classified as subarkose—arkosic sandstones. Feldspar and rock fragment make up the next abundant framework component as observed during petrographic analysis and this was used in concert with the quartz composition for characterization of the paleoclimate content and paleotectonic settings. Suttner et al. (1981) were able to isolate climate as a compositional determinant of the control of the mineralogical composition of terrigenous rocks. In their study using Holocene sands, they considered both humid and arid settings and their findings were a classical model for paleoclimatic reconstruction. In ancient analogues, the formation of arkoses suggests preservation of feldspars during source area weathering (Boggs, 1992; Ullah et al. 2006). This occurs due to the prevalent tectono-geomorphologic and/or climatic conditions of the source

area (cold/arid climatic conditions inhibit chemical weathering and rapid uplifts support faster erosion before labile minerals decompose in warmer/humid climatic settings). Based on the percentage composition of quartz, feldspar and rock fragment, as shown in Fig. 11b, the sandstones deposited within intermediate phases of metamorphic humid and plutonic humid climate (Suttner et al. 1981). Also, using the fields of Dickinson and Suczek (1979), a continental block provenance comparable to the present-day basement complex areas of Oban Massif and southwestern Nigeria basement rocks characterized the tectonic setting during deposition of Awi Formation and Lokoja Formation, respectively (Fig. 11c, d). Cratonic interior and uplifted basement is similar to the settings of the Oban Massif before the final breakup of Gondwanaland.

#### 4.4 Heavy mineral assemblages

The result of the heavy mineral analysis is presented in Table 5. The result shows the presence of zircon, tourmaline, and rutile along with garnet, apatite, and sillimanite. A total of about 7183 grains was counted while

**Fig. 10** **a, b** Photomicrograph of subangular to subrounded framework grains (quartz and plagioclase) of sandstones of Lokoja Formation, **c, d** polycrystalline quartz, bending mica flakes, moderately sorted



2520 (35.08%) were opaque constituting undifferentiated magnetite, ilmenite etc., the non-opaque mineral grains constituted the dominant fraction (64.9%). The grains are angular and characterized by sharp edges, most labile minerals are depleted in the assemblages leaving more resistant (ultra-stable) minerals in the assemblage (Fig. 12a–d). The presence of moderately stable garnet and sillimanite suggests a short period of transportation of samples from their source area. The presence of heavy minerals such as zircon, tourmaline, and apatite indicate an igneous origin while the presence of garnet and sillimanite indicate a metamorphic origin (Kumari et al. 2020; Okon & Essien, 2015). ZTR index computed for the samples show a range from 54 to 82% (av = 70.7%) and suggests that the samples are mineralogically sub-mature (Hubbert, 1962).

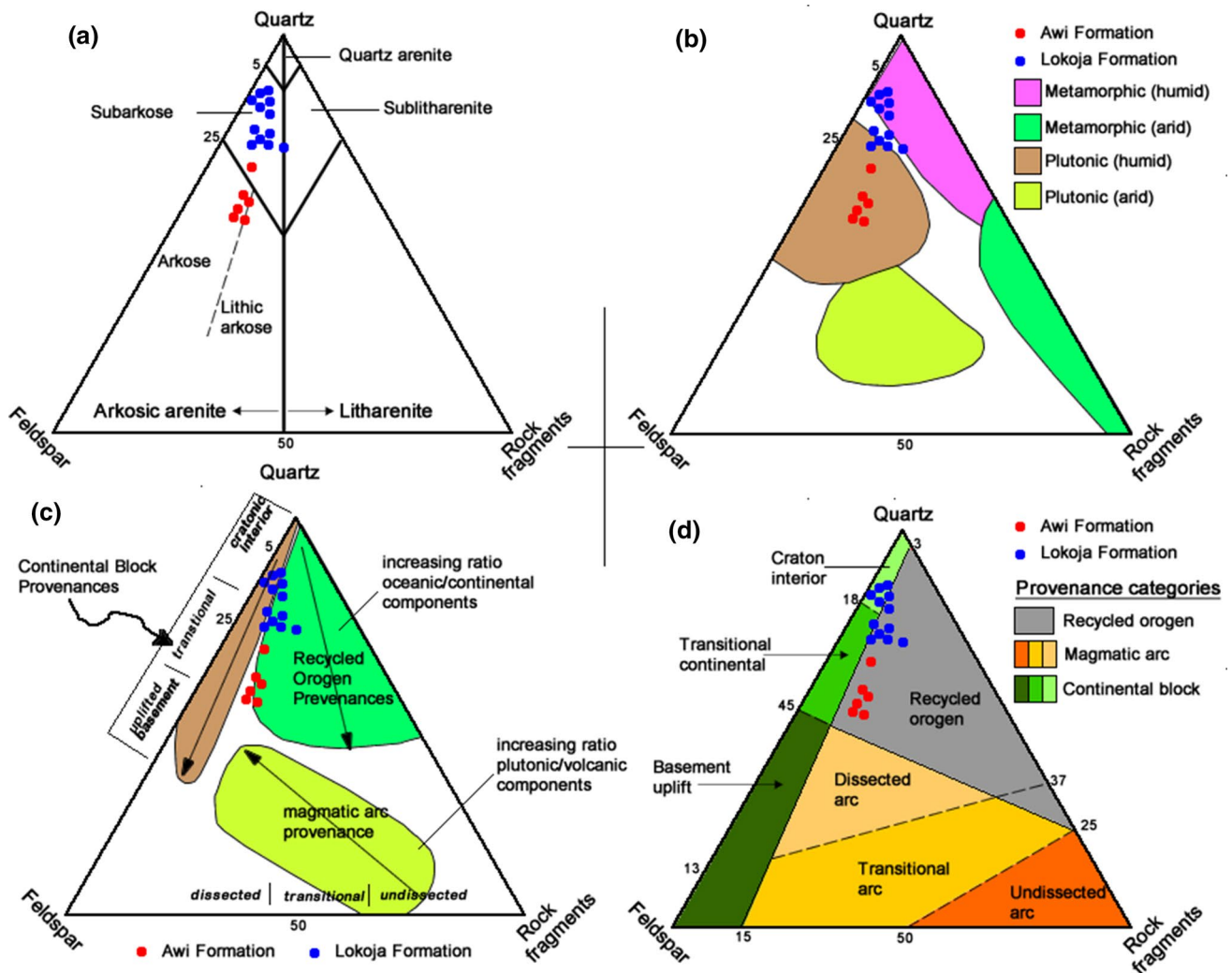
A quick source material characterization was conducted by comparing the heavy mineral constituents of this study with the identified source material-heavy mineral assemblages of Feocodecido (1955) and the findings suggest that igneous to metamorphism source, possibly

of high-grade metamorphism are the most likely source area for the sandstones. With the predominance of pink variety tourmaline over blue variety, an acid (felsic) igneous source is favoured as opposed to pegmatitic source (Feocodecido, 1955; Okon & Essien, 2015).

#### 4.5 Mineralogy

The summary of the results of the analysis is presented in Table 6. The representative clay-sized samples were studied by X-ray diffraction and the curves were interpreted by comparing notable intensity peaks with those for standard minerals established by Carrol (1970) for qualitative determination of mineral presence. The origin of clay mineral assemblages in marine sediments may be traced to one of two principal sources: terrigenous detritus (emphasizes the provenance information) and authigenic process (alteration of volcanic sea floor basement or hydrothermalism). Fluvial processes also account for major control on the dispersion of clay minerals to the continental margins, where other processes transmit the clay components into the depositional





**Fig. 11** **a** Mineralogical classification of the Awi and Lokoja sandstones; **b** Paleoclimatic setting of Awi and Lokoja Formations (fields after Suttner et al. 1981); **c** triangular plot for characterization of

provenance of Awi and Lokoja Formations (after Dickinson & Suczek, 1979); **d** triangular plot of Awi and Lokoja sandstones (after Dickinson et al. 1983)

basin (Adatte et al. 2002; Das et al. 2013; Rea & Leinen, 1988). Impacts of climate change are related to continental weathering rates and runoff, influences soil formation and transport of terrigenous material into the sea.

The effects of diagenetically introduced clay minerals are considered insignificant and thus where present in the assemblages, they may easily be isolated during interpretation. Certain ratios of clay mineral species are proxies for paleoclimatic conditions measured by their intensity and susceptibility to weathering at their source areas (Chutia et al. 2020; Dou et al. 2010; Grim, 1968; Zhifei et al. 2003). The presence of kaolinite in excess of illite may indicate warm climatic conditions because intense chemical weathering is ensued under warm and humid climate, whereas illite commonly results from physical weathering under cool and dry climate. Clay mineral composition of Awi Formation

includes kaolinite (40.10%), illite (31.45%), mixed layer kaolinite: illite (11.70%) with an overall abundance of kaolinite (diffractograms are presented as supplementary materials). The non-clay mineral assemblage include quartz (3.37%) and muscovite (3.69%).

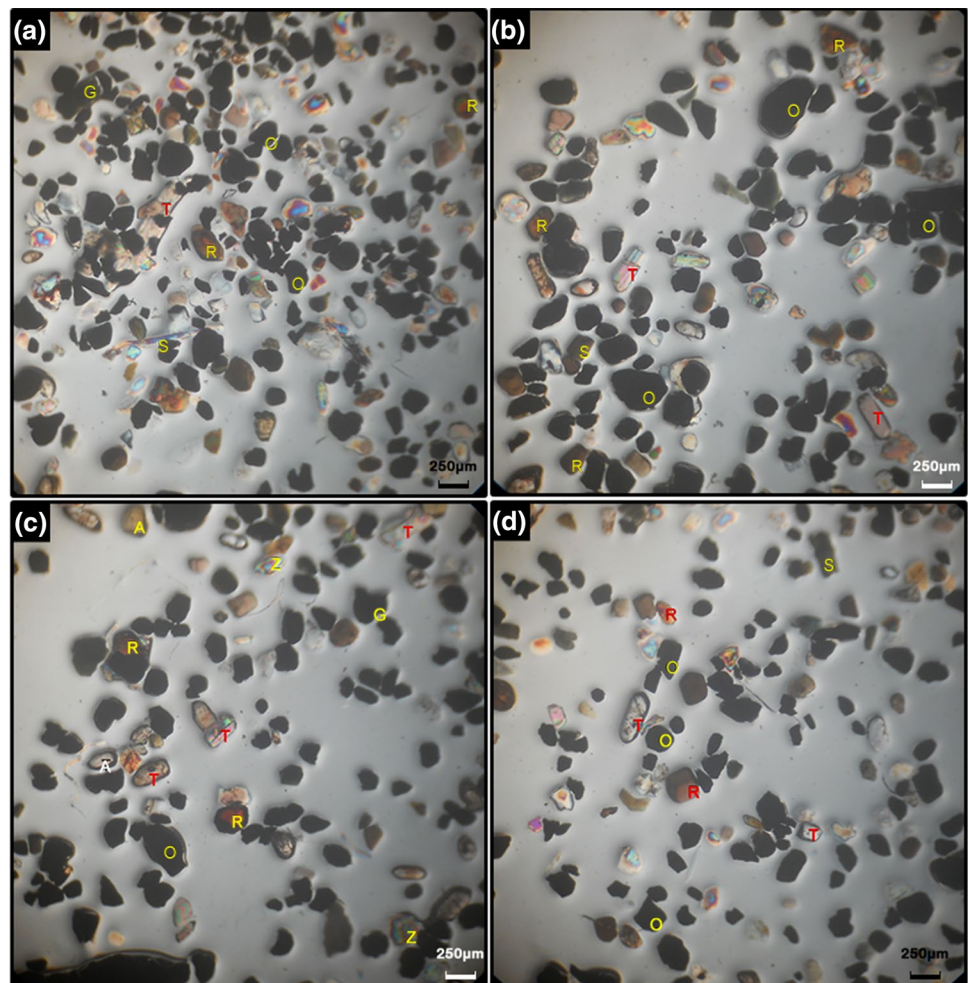
In the Lokoja Formation the dominant clay mineralogical assemblage is kaolinite (33.31%) and montmorillonite (4.92%), although it was suspected that the montmorillonite may eventually be halloysite, following a more detailed clay fraction analysis such as clay specialization to confirm its presence and quartz (50.38) as the only non-clay mineral constituent. There are also mixed clay:non-clay mineral species in the association, for instance, quartz:illite, quartz:kaolinite, quartz:muscovite, and kaolinite:muscovite in the Awi Formation assemblage and quartz:kaolinite, kaolinite:quartz and quartz:montmorillonite in the Lokoja

**Table 5** Result of heavy mineral analysis

Sample ID	Z	R	T	Sil	Gar	Apa	others	Opa	N-opa	Z+T+R	ZTR index
A1-1	77	61	82	24	30	10	13	178	297	220	74
A1-2	68	55	91	20	41	7	22	150	304	214	70
A1-3	76	88	76	35	23	14	12	216	324	240	74
A1-4	88	67	64	46	45	21	43	205	374	219	59
A2-2	71	61	63	60	53	23	31	217	362	195	54
A4-1	50	33	67	24	12	14	16	106	216	150	69
L10-2	38	26	36	15	15	12	12	98	154	100	65
L10-4	46	27	35	15	13	9	9	78	154	108	70
L9-5a	36	58	47	15	12	13	14	92	195	141	72
L9-5b	58	46	37	14	14	9	15	69	193	141	73
L9-5c	56	46	41	15	13	14	38	124	223	143	64
L11-1	87	66	54	12	15	13	40	143	287	207	72
L11-2	76	64	65	13	13	14	54	164	299	205	69
L11-3	76	77	56	14	13	12	19	107	267	209	78
L11-4	56	46	77	15	13	12	32	157	251	179	71
L11-6	83	66	59	9	14	6	21	133	258	208	81
L11-7	76	81	56	15	12	8	29	129	277	213	77
L11-5	56	53	77	13	9	5	15	154	228	186	82
Sum	1174	1021	1083	374	360	216	435	2520	4663		

Z zircon, T tourmaline; R rutile, Sil sillimanite; Gar garnet; Apa apatite; Opa opaque; N opa-non-opaque

**Fig. 12** Photomicrograph showing heavy minerals from Awi Formation (a, b) and Lokoja Formation (c, d), note the pink-brownish tourmaline and abundant opaque minerals (T tourmaline, R rutile, O opaque, S sillimanite, G garnet)





**Table 6** Modal composition for minerals present in clay-size fractions

Sample no	Types and percentage of minerals available
Awi/C2	Quartz (1.74%), Illite (47.67%), Quartz: Illite (50.58%)
Awi/C3	Kaolinite (52.54%), Quartz (0.88%), Illite (15.23%), Kaolinite: Illite (11.70%), Quartz: Illite (15.45%), Quartz: kaolinite: Illite (4.19%)
Awi/C4	Kaolinite (27.66%), Quartz (7.51%), Muscovite (3.69%), Quartz: Kaolinite (5.53%), Quartz: Muscovite (1.70%), Kaolinite: Muscovite (14.32%), Quartz: Kaolinite: Muscovite (39.57%)
Agb/sk1	Kaolinite (51.23%), Quartz (27.16%), Quartz: Kaolinite (21.60%)
Agb/sk2	Kaolinite (1.9%), Quartz (91.37%), Kaolinite: Quartz (6.73%)
Agb/sk3	Kaolinite (46.80%), Quartz (32.61%), Montmorillonite (4.92%)

Formation. Most of the clay minerals present may be attributed to the weathering of feldspars and other rock-forming minerals. Birkeland (1984) noted that illite may be derived from the alteration of micas under warmer and wetter conditions and this may have been responsible for elevated illite in the samples.

#### 4.6 Depositional environment and provenance

Although Madukwe (2017) carried out granulometric analysis of the Lokoja and identified fluvial influence but eventually concluded that shallow marine beach processes were responsible for the deposition of the sandstone. Olawoki et al. (2018) further attributed turbiditic processes to have been in place during the deposition of the Lokoja Formation. Complete fluvial depositional settings were suggested by Omali et al. (2011). The differences in depositional settings outlined for the Lokoja formation sparked interest among sedimentologists and a review of depositional processes was carried out and compared with those of the Awi Formation. Textural studies suggest fluvio-deltaic settings as well as field observations and sedimentary structures. Marine influences in the basin were only observable during the deposition of Patti (or Ahoko Formation) and younger sediments in the Bida Basin (Akande et al. 2005; Ojo & Akande, 2003; Rahaman et al. 2019). Rekindled interests in the evaluation of the hydrocarbon potentials of the Bida Basin is based on the need to increase the reserve in the country through studies of inland basins. Therefore, a clear understanding the depositional processes that ensued during the stratigraphic evolution of the Bida basin is important (Akande et al. 2005; Obaje et al. 2004, 2013; Olawoki et al. 2018; Rahaman et al. 2019). The environment of deposition for the Lokoja Formation based on field observations is dominantly fluvial (alluvial—meandering) with some tidal influence (presence of flaser bedding and mud drapes) especially in the Awi Formation. This is in agreement with previous works, such as Adel-eye and Fayose (1978), Olugbemi and Nwajide (1997),

Nton (1999), Ojo and Akande (2003), Akande et al. (2005), Boboye and Okon (2014) and Okon (2015). While the Awi Formation constitutes light brown to reddish-brown, agitated (high energy), angular – subrounded conglomeratic, poorly sorted and strongly fine skewed sandstones with floodplain mudstone deposits, exhibiting an overall fining upward succession, the Lokoja Formation is light brown to white, conglomeratic, poorly sorted, friable sandstones. There is variation in thickness from bed to bed. While the Awi Formation is stratigraphically succeeded by shallow marine platform carbonates (Mfamosing Limestone), the Lokoja Formation is succeeded by dark grey-black marine clastics of the Ahoko Formation of Rahaman et al. (2019). The succeeding beds were not considered in this study.

## 5 Conclusion

The sedimentological characteristics and mineralogical composition of the sediments depict clays that originate from weathering of feldspar and deposition in continental settings. Both the Awi Formation and Lokoja Formation, though of different ages, are arkosic to sub-arkosic arenites, mineralogically sub-mature, and deposited within continental block tectonic settings (passive margin/rift shoulders), under humid climate and in close proximity to the marine environment. Paleoclimatic settings were affirmed from mineralogical and modal analyses of the sediments. Analysis shows that continental block provenance and recycled orogen analogous to the present-day Oban Massif and North and Central Nigerian crystalline basement complex may be the major contributors to sediments in the Awi Formation and Lokoja Formation respectively.

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**Author contributions** All authors contributed to the study conception and design. Material preparation, data collection and analyses were performed by OKJ, OK, and OEE under close supervision of OKB, OA. The first draft of the manuscript was written by OKJ, OK; and all authors read, commented, discussed, and approved the contents of the final manuscript.

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**Availability of data and materials** All data set used in this manuscript are presented as tables and reported in the results section. However, details of tables presented as summaries in the manuscript are presented as supplementary data.

## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states clearly that this work is original, not under review in any journal and we (the authors) all declare that we have no competing interests.

## References

- Adamu, C. I., Okon, E. E., & Inyang, D. O. (2020). Granulometry, heavy mineral and geochemical studies of stream sediments around Bula, Dass district, northeast Nigeria. *Global Journal of Geological Sciences*, *18*, 63–73. <https://doi.org/10.4314/gjgs.v18i1.6>
- Adatte, T., Keller, G., & Stinnesbeck, W. (2002). Late Cretaceous to early Paleocene climate and sea-level fluctuations: The Tunisian record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *178*, 165–196.
- Adeleye, D. R., & Dessauvagie, T. F. G. (1972). Stratigraphy of the Niger embayment near Bida, Nigeria. In T. F. J. Dessauvagie & A. J. Whiteman (Eds.), *African Geology* (pp. 181–186). Ibadan.
- Adeleye, D. R., & Fayose, E. A. (1978). Stratigraphy of the type section of Awi Formation, Odukpani area southeastern Nigeria. *Journal of Mining and Geology*, *15*, 33–37.
- Akande, S. O., Ojo, O. J., Erdtmann, B. D., & Hetenyi, M. (2005). Paleoenvironments, organic petrology and Rock-Eval studies on source rock facies of the Lower Maastrichtian Patti Formation, southern Bida Basin, Nigeria. *Journal of African Earth Science*, *41*, 394–406.
- Angusamy, N., & Rajamanickam, G. V. (2006). Depositional environment of sediments along the southern coast of Tamil Nadu, India. *Oceanologia*, *48*(1), 87–102.
- Baiyegunhi, C., Liu, K., & Gwavava, O. (2017). Grain size statistics and depositional pattern of the Ecca Group sandstones, Karoo Supergroup in the Eastern Cape Province, South Africa. *Open Geosciences*, *9*, 554–576. <https://doi.org/10.1515/geo-2017-0042>
- Birkeland, P. W. (1984). *Soils and geomorphology* (Oxford University Press).
- Boboye, O. A., & Okon, E. E. (2014). Sedimentological and geochemical characterization of the Cretaceous strata of Calabar Flank, southeastern Nigeria. *Journal of African Earth Sciences*, *99*, 427–441. <https://doi.org/10.1016/j.jafrearsci.2014.04.035>
- Boggs, S. Jr., (1992). *Sedimentary Petrology* (Blackwell Scientific Publications).
- Braide, S. P. (1992). Geological development, origin and energy mineral resources Potential of Lokoja Formation in the Southern Bida Basin. *Journal of Mining and Geology*, *28*, 33–44.
- Carroll, D. (1970). Clay minerals: A guide to their X-ray identification. *Geological Society of America Special Paper*, *126*, 80p.
- Chutia, A., Taye, C. D., Daimari, J., & Chutia, D. (2020). Petrography and clay mineralogical study of the Siwalik group of rocks exposed along Pasighat-Mariyang Road Section, East Siang District, Arunachal Pradesh, Northeast India. *Journal Geological Society of India*, *95*, 263–272. <https://doi.org/10.1007/s12594-020-1424-1>
- Cullers, R.L., Baret, T., Carlson, R. & Robinson, B. (1987). Rare earth element and mineralogical changes in Holocene soil and stream sediment: a case study in the Wet Mountains. Colorado, USA. *Chemical Geology*, *63*(3–4), 275–295.
- Das, S. S., Rai, A. K., Akaram, V., Verma, D., Pandey, A. C., Dutta, K., & Ravi Prasad, G. V. (2013). Paleoenvironmental significance of clay mineral assemblages in the southeastern Arabian Sea during last 30 kyr. *Journal of Earth System Science*, *122*(1), 173–185.
- Dessauvagie, T. F. G. (1975). Explanatory note to the geological map of Nigeria, scale 1: 1,000,000. *Journal of Mining and Geology*, *9*(12), 328.
- Dickinson, W. R., Bread, L. S., Brakenridge, G. R., Erjavec, J. L., Ferguson, R. C., Inmam, K. F., Knepp, R. A., Linberg, F. A., & Ryberg, P. T. (1983). Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin*, *94*, 222–235.
- Dickinson, W. R., & Suczek, C. A. (1979). Plate tectonics and sandstone compositions. *American Association of Petroleum Geology Bulletin*, *63*, 2164–2182.
- Dou, Y., Yang, S., Liu, Z., Clift, P. D., Yu, H., Berne, S., & Shi, X. (2010). Clay mineral evolution in the central Okinawa Trough since 28 ka: Implications for sediment provenance and paleoenvironmental change. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *288*, 108–117.
- Edet, J. J., & Nyong, E. E. (1993). Depositional environments, sea-level history and paleobiogeography of the late Campanian-Maastrichtian on the Calabar Flank, SE Nigeria. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *102*, 161–175.
- Eker, C. S., & Ari, U. V. (2020). Geochemistry of the Middle Jurassic sediments in Gümüşhane, north-eastern Turkey: Implications for weathering and provenance. *Geological Journal*, *55*, 4954–4976.
- Eker, C. S., & Korkmaz, S. (2011). Mineralogy and whole rock geochemistry of late Cretaceous sandstones from the eastern Pontides (NE Turkey). *Neues Jahrbuch Für Mineralogie*, *188*(3), 235–256.
- Eker, C. S., Sipahi, F., & Kaygusuz, A. (2012). Trace and rare earth elements as indicators of provenance and depositional environments of Lias Cherts in Gumushane, NE, Turkey. *Chemie Der Erde*, *72*, 167–177.
- Essien, N. U., Ilori, O. A., Okon, E. E., & Njoku, N. S. (2016). Textural Characteristics and Depositional Processes of Sediments from a 47 km Transect in the Niger Delta, Southern Nigeria. *Journal of Geography, Environment and Earth Science International*, *7*(1), 1–11. <https://doi.org/10.9734/JGEEESI/2016/27919>
- Essien, N. U., & Okon, E. E. (2016). Sedimentary processes and depositional environments of part of the Benin Formation in the Calabar Flank, Southeastern Nigeria. *British Journal of Applied*

- Science and Technology*, 18(5), 1–10. <https://doi.org/10.9734/BJAST/2016/31138>
- Essien, N. U. & Okon, E. E. (2019). Sedimentary processes and environments of deposition of part of the Benin Formation, South-eastern Nigeria. In: Ostad-Ali-Askari, K. (Ed.), *Advances in Applied Science and Technology*, vol. 1 (pp. 20–32). <https://doi.org/10.9734/bpi/aast/v1>.
- Fadiya, S. L. (2015). Particle size analysis of some sidewall cores from KU-1 Well, Offshore Benin Basin, Nigeria. *Ife Journal of Science*, 17(2), 363–381.
- Feoodecido, G. (1955). Heavy mineral techniques and their application to Venezuelan stratigraphy". *American Association Petroleum Geologists Bulletin*, 40(5), 984–1000.
- Folk, R. L., & Ward, W. L. (1957). Brazus River bar: a study of the significance of grain size parameters. *Journal of Sedimentary Petrology*, 27, 3–27.
- Friedman, G. M. (1961). Distinction between dune, beach and river sands from their textural characteristics. *Journal of Sedimentary Petrology*, 31, 514–529.
- Friedman, G. M. (1962). Dynamic processes and statistical parameters compared for size frequency distribution of beach river sands. *Journal of Sedimentary Petrology*, 37, 327–354.
- Friedman, G. M. (1967). Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands. *Journal of Sedimentary Petrology*, 37(2), 327–354.
- Ganesh, B. Naidu, A.G.S.S. Jagannadha Rao, M. Karuna Karudu T. & Avatharam, P. (2013). Studies on textural characteristics of sediments from Gosthani River Estuary—Bheemunipatnam, A.P., East Coast of India. *Journal of Indian Geophysical Union*, 17(2), 139–151.
- Gees, R. A. (1965). Moment measures in relation to the depositional environments of sands. *Eclogae Geologicae Helveticae*, 58, 209–213.
- Grim, R. E. (1968). *Clay mineralogy* (McGraw Hill).
- Hubbert, J. F. (1962). A Zircon-Tourmaline-Rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones. *Journal of Sedimentary Petrology*, 32, 440–450.
- Inyang, D. O., Itam, A. E., & Okon, E. E. (2014). Granulometry and pebble morphometry of an exposed section of the Benin Formation around Okurikang and environs, Southeastern Nigeria. *International Journal of Natural and Applied Sciences (IJNAS)*, 9(1 & 2), 45–52.
- Kermani, S., Boutiba, M., Boutaleb, A., & Fagel, N. (2015). Distribution of heavy and clay minerals in coastal sediment of Jijel, East of Algeria: indicators of sediment sources and transport and deposition environments. *Arabian Journal of Geosciences*. <https://doi.org/10.1007/s12517-015-2155-2>.
- King, L. C. (1950). Outline and distribution of Gondwanaland. *Geological Magazine*, 87, 353–359.
- Kumari, K. Gandhi, M. S., Vamsi, K. S., Das, P., & Basha, U. I. (2020). Characterization of sedimentary environment, provenance and distribution of heavy minerals along the Tamil Nadu shoreline, East coast of India. *Journal of Sedimentary Environments*. <https://doi.org/10.1007/s43217-020-00030-7>.
- Madukwe, H. Y. (2017). Granulometric study of the Lokoja Sandstone, Mid Niger Basin, Nigeria. *Review of Environment and Earth Sciences*, 4(1), 12–26. <https://doi.org/10.18488/journal.67/2017.4.1/67.1.12.26>
- Mange, M. A., & Maurer, W. H. (1992). *Heavy mineral in colour*. Chapman and Hall.
- Martin, L. R. (2003). Recent sediments and grain size analysis. *Gravel*, 1, 90–105.
- Mason, C. C., & Folk, R. L. (1958). Differentiation of Beach, Dune and Aeolian flat environments by size analysis". *Journal of Sedimentary Petrology*, 28, 211–226.
- Murat, R. C. (1972). Stratigraphy and Paleogeography of the Cretaceous Lower Tertiary and Southern Nigeria. In T. F. J. Dessauvage & A. J. Whiteman (Eds.), *African Geology* (pp. 215–226). Ibadan.
- Nordstrom, K. F. (1977). The use of grain size statistics to distinguish between high-and moderate-energy beach environments. *Journal of Sedimentary Research*, 47(3), 1287–1294. <https://doi.org/10.1306/212F731F-2B24-11D7-8648000102C1865D>.
- Nton, M. E. (1999). Sedimentology and depositional environment of Awi Formation, Calabar Flank, Southeastern Nigeria. *Journal of Mining and Geology*, 33(1), 23–36.
- Nwajide, C. S. (2013). *Geology of Nigeria's sedimentary basins*. CSS Press.
- Nyong, E. E., & Ramanathan, R. M. (1985). A record of oxygen deficient Paleoenvironments in the Cretaceous of the Calabar flanks, S. F. Nigeria. *Journal of African Earth Sciences*, 3(4), 455–460.
- Obaje, N. G., Balogu, D. O., Idris-Nda, A., Goro, I. A., Ibrahim, S. I., Musa, M. K., Dantata, S. H., Yusuf, I., Mamud-Dadi, N., & Kolo, I. A. (2013). Preliminary integrated hydrocarbon prospectivity evaluation of the Bida Basin in North Central Nigeria. *Petroleum Technology Development Journal*, 3(2), 36–65.
- Obaje, N. G., Wehner, H., Scheeder, G., Abubakar, M. B., & Jauro, A. (2004). Hydrocarbon prospectivity of Nigeria's inland basins: from the viewpoint of organic geochemistry and organic petrology. *American Association of Petroleum Geologists Bulletin*, 87, 325–353.
- Ocheli, A., Okoro, A. U., Ogbe, O. B., & Aigbadon, G. O. (2018). Granulometric and pebble morphometric applications to Benin Flank sediments in western Anambra Basin, Nigeria: proxies for paleoenvironmental reconstruction. *Environmental Monitoring and Assessment*, 190, 286–303. <https://doi.org/10.1007/s10661-018-6637-z>
- Ojo, O. J., & Akande, S. O. (2003). Facies relationships and depositional environments of the Upper Cretaceous Lokoja Formation in the Bida Basin, Nigeria. *Journal of Mining and Geology*, 39, 39–48.
- Ojo, O. J., & Akande, S. O. (2013). Petrographic facies provenance and paleoenvironment of the Lokoja Formation, southern Bida Basin, Nigeria. *Journal of Mining and Geology*, 49(2), 93–109.
- Ojo, S. B. & Ajakaiye, D. E (1989). Preliminary interpretation of gravity measurements in the Mid-Niger Basin area, Nigeria. In: Kogbe, C. A. (Ed.), *Geology of Nigeria* (pp. 347–358), 2nd edn. Elizabethan Publishers.
- Okon, E.E. (2011). Sedimentology and Geochemical characterization of the Cretaceous sediments of the Calabar Flank, South-eastern Nigeria. *Unpublished M.Sc Thesis*. University of Ibadan.
- Okon, E. E. (2015). Sedimentologic characteristics and provenance studies of Awi Formation, Calabar Flank, South-Eastern Nigeria. *Journal of Mining and Geology*, 51(2), 121–138.
- Okon, E. E., & Essien, N. U. (2015). Depositional processes and provenance determination using grainsize analysis and heavy mineral assemblages of surficial sediment and stream sediment samples from Iwere-Ile and its environs. *International Journal of Scientific and Engineering Research*, 6(11), 1238–1246.
- Okon, E. E., Essien, N. U., & Adeyemi, G. O. (2017). Geochemistry of Sandstones of AWI Formation, South-eastern Nigeria: Implication for Weathering, Provenance and Tectonic Settings. *International Journal of Science and Technology*, 6(4), 742–755.
- Olawoki, O.A., Coker, S.J., Rahaman, M.A., Fadiya, S.L. & Bale, R.B. (2018). Studies assess central nigeria's Bida Basin potential. *Oil and Gas Journal*. <https://www.ogj.com/articles/print/volume-116/issue-6/exploration-development/studies-assess-central-nigeria-s-bida-basin-potential.html>. Accessed 20th Sep 2018.
- Olugbemiro, R., & Nwajide, C. S. (1997). Grain size distribution and particle morphogenesis as signatures of depositional environments

- of Cretaceous (non-ferruginous) facies in the Bida Basin, Nigeria. *Journal of Mining and Geology*, 33, 89–101.
- Omali, A. O., Imasuen, O. I., & Okiotor, M. E. (2011). Sedimentological characteristics of Lokoja Sandstone exposed at Mount Patti, Bida Basin, Nigeria. *Advances in Applied Science Research*, 2(2), 227–245.
- Opreatu, G., Oaie, G., & Paun, F. (2007). The dynamic significance of the grain size of sediments transported and deposited by the Danube. *GeoEcoMarina*, 13, 111–119.
- Petters, S. W. (1980). Biostratigraphy of Upper Cretaceous Foraminifera of the Benue Trough. *Nigerian Journal of Foraminiferal Research*, 10, 191–204.
- Petters, S.W., Nyong, E.E., Akpan, E.B & Essien, N.U. (1995). *Lithostratigraphic revision of the Calabar Flank, South East Nigeria: Proceedings of the 31st Annual Conference of the Nigerian Mining and Geosciences Society, Calabar.*
- Petters, S.W., Zaborski, P. M.P., Essien, N.U., Nwokocha, K.D. & Inyang, D. (2010). *Geological excursion guidebook to the Cretaceous of the Calabar Flank, southeast Nigeria. Nigerian Mining and Geosciences Society 46th Annual Conference "Calabar 2010"*. Shamba Grafitech Studio.
- Rahaman, M. A. O., Fadiya, S. L., Adekola, S. A., Coker, S. J., Bale, R. B., Olawoki, O. A., Omada, I. J., Obaje, N. G., Akinsanpe, O. T., Ojo, G. A., & Akande, W. G. (2019). A revised stratigraphy of the Bida Basin, Nigeria. *Journal of African Earth Sciences*, 151, 67–81. <https://doi.org/10.1016/j.jafrearsci.2018.11.016>
- Rahaman, M. A. O., Fadiya, S. L., Adekola, S. A., Coker, S. J., Bale, R. B., Olawoki, O. A., Omada, I. J., Obaje, N. G., Akinsanpe, O. T., Ojo, G. A., & Akande, W. G. (2020). The response to the rebuttal on the revised stratigraphy of the Bida Basin, Nigeria: New observations. *Journal of African Earth Sciences*, 172, 1–8. <https://doi.org/10.1016/j.jafrearsci.2020.104018>
- Rajasekhara Reddy, D., Karuna Karudu, T., & Deva Varma, D. (2008). Textural characteristics of south western part of Mahanadi Delta, east coast of India. *Journal of Indian Association of Sedimentologists*, 27(1), 111–121.
- Rajesh, E., Anbarasu, K., & Rajamanickam, G. V. (2007). Grain size distribution of silica sand in and around Marakkanam coast of Tamil Nadu. *Journal of the Geological Society of India*, 69, 1361–1368.
- Ramanathan, A. L., Rajkumar, K., Majumdar, J., Singh, G., Behera, P. N., Santra, S. C., & Chidambaram, S. (2009). Textural characteristics of the surface sediments of a tropical mangrove Sundarban ecosystem, India. *Indian Journal of Marine Sciences*, 38(4), 397–403.
- Rea, D. K., & Leinen, M. (1988). Asian aridity and the zonal westerlies: Late Pleistocene and Holocene record of eolian deposition in the Northwest Pacific Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 66, 1–8.
- Reyment, R. A. (1965). *Aspects of the geology of Nigeria*. University of Ibadan Press.
- Sahu, B. K. (1964). Depositional mechanism from the size analysis of elastic sediments. *Journal of Sedimentary Petrology*, 34(1), 73–83.
- Sutherland, R. A., & Lee, C. T. (1994). Discrimination between coastal sub-environments using textural characteristics. *Sedimentology*, 41, 1133–1143.
- Suttner, L. J., Basu, A., & Mach, G. H. (1981). Climate and Origin of quartz-arenites. *Journal. Sedimentary Petrology*, 51, 1235–1246.
- Taylor, S. R., & McLennan, S. M. (1985). *The Continental crust: Its composition and evolution* (p. 312). Blackwell Scientific Publishing.
- Ullah, K., Arif, M., & Shah, M. T. (2006). Petrography of sandstones from the Kamlial and Chinji Formations, Southwestern Kohat Plateau, NW Pakistan: Implications for Source Lithology and Paleoclimate. *Journal of Himalayan Earth Sciences*, 39, 1–13.
- Vakalis, I., Ananiadis, G., Kontopoulos, N., & Zeliidis, A. (2004). Grain size statistical parameters and palaeoflow velocity measurements of the Tertiary Pindos Foreland Basin turbidites. *Bulletin of the Geological Society of Greece*, 34, 717–724.
- Visher, G. A. (1969). Grain size distributions and depositional processes. *Journal of Sedimentary Petrology*, 39, 1074–1106.
- Whiteman, A. J. (1982). *Nigeria: Its Petroleum Geology, Resources and Potential*. Graham and Trotman.
- Wronkiewicz, D. J., & Condie, K. C. (1987). Geochemistry of Archean shales from the Witwatersrand Supergroup, South Africa: source area weathering and provenance. *Geochimica Et Cosmochimica Acta*, 51(9), 2401–2416.
- Wronkiewicz, D. J., & Condie, K. C. (1989). Geochemistry and provenance of sediments from the Pongola Supergroup, South Africa: evidence for a 3.0 Ga-old continental craton. *Geochimica Et Cosmochimica Acta*, 53(7), 1537–1549.
- Zaborski, P. M. (1998). A review of the Cretaceous systems in Nigeria. *African Geoscience Reviews*, 5(4), 385–483.
- Zhifei, L., Trentesaux, A., & Clemens, S. C. (2003). Quaternary clay mineralogy in the northern South China Sea (ODP site 1146): implications for oceanic current transport and east Asian monsoon evolution. *Science China (series d)*, 46(12), 1223–1235.

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