https://dx.doi.org/10.4314/dujopas.v12i1d.3
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol.12 No. 1d March 2026*

Geology and Sedimentology of Mulke and Environs, Northern Benue Trough, Northeastern Nigeria

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Abstract
This paper investigates the geological and sedimentological characteristics of Mulke and its environs within the Yola Arm of the Northern Benue Trough, northeastern Nigeria. The study involved field mapping, petrographic and granulometric analysis to assess depositional processes and the sedimentary environment. Geological field mapping identified the Bima Sandstone as the main lithologic unit. This sandstone exhibits a variety of sedimentary structures, including parallel bedding, planar cross-bedding, massive bedding, graded bedding, and ripple marks, all of which are consistent with tractional depositional processes. A petrographic analysis of five thin sections revealed that the sandstone is predominantly composed of quartz, with minor amounts of feldspar and clay minerals. The grains are mostly angular to sub-rounded, and the intergranular contacts indicate that it can be classified as quartz arenite, reflecting a high degree of textural and compositional maturity. Granulometric analysis of twelve (12) representative samples showed grain sizes ranging from very coarse to medium sand (−0.48 to 1.45 Φ), with sorting values between 0.81 and 1.39 Φ, suggesting a moderate to poor sorting. The skewness values vary from 0.03 to 0.34, indicating distributions that are nearly symmetrical to fine-skewed, while kurtosis values range from 0.27 to 1.49, which corresponds to very platykurtic to leptokurtic sand. Bivariate plots and log-probability curves indicate that sediment transport is mainly driven by traction and saltation under different flow conditions. Based on the gathered data, the study concludes that the sandstone in the area was deposited in a fluvial environment.

Keywords: Mulke, Bima Sandstone, Sedimentology, Sedimentary structures, Fluvial Environment.

INTRODUCTION
The Bima Sandstone, known as the continental sedimentary succession in the Chad Basin and Northern Benue Trough of Nigeria, represents the oldest sedimentary unit in these regions. Predominantly composed of arkosic to quartz arenite sandstones, its depositional structures have prompted extensive discussions regarding its provenance and environment of deposition. Regional geological studies of the Bima Formation commenced with Falconer (1911) and were subsequently enhanced by Carter et al. (1963). The tectonic development of the Benue Trough and its impact on the Bima Formation were further analyzed by Burke et al. (1971). More recent studies by Haruna et al. (2012; 2013) and Opeloye (2012) demonstrated that the composition and texture of the Bima Sandstone reflect sediment supply from surrounding crystalline massifs and tectonic controls on sedimentation within the basin. Despite numerous regional studies conducted on the Bima Formation, sedimentological research that combines field observations with petrographic and granulometric analysis has not been carried out in some places, particularly Mulke and its environs. A focused study

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like this will help us understand the depositional processes and environments, as well as improve our stratigraphic knowledge of the basin.

This work will therefore analyze the geological and sedimentological characteristics of the Bima sandstone in Mulke to understand its depositional conditions, which is crucial for reconstructing the depositional environment, identifying sediment sources, interpreting stratigraphy and assessing resource potential.

Geologic setting

The Benue Trough is an important rift basin situated in central West Africa, extending across Nigeria predominantly in a NNE–SSW orientation for approximately 1,000 kilometers and averaging about 150 kilometers in width. To the south, it is bordered by the northern edge of the Niger Delta, while the Chad Basin is located to the north (Obaje, 2009) (Figure 1a). This trough contains up to 6,000 meters of sedimentary layers from the Cretaceous to Tertiary periods, with the pre–mid-Santonian deposits undergoing significant compressional deformation, resulting in extensive folding, faulting, and uplift. The mid-Santonian tectonic episode represents the most critical phase of deformation in the history of the Benue Trough, producing numerous anticlines and synclines along its length (Benkhelil, 1989). Subsequently, tectonic and magmatic activities led to a westward shift in the depositional axis, resulting in the formation of the Anambra Basin as a post-deformational extension of the Lower Benue Trough, which is filled with Campanian–Maastrichtian to Eocene sediments (Akande and Erdtmann, 1998). For clarity, the Benue Trough is categorized into Lower, Middle, and Upper segments, based on their primary depocentres rather than distinct structural boundaries. The area of interest is located within the Yola Arm sub-basin of the Northern Benue Trough. Sedimentation in this sub-basin commenced with the continental Lower Cretaceous Bima Formation, followed by the Cenomanian transitional marine Yolde Formation, and concluded with late Cenomanian to Santonian marine units, which encompass the Dukul, Jessu, and Sekuliye Formations, along with the Numanha Shales and Lamja Sandstones (Carter et al., 1963; Abubakar, 2006).

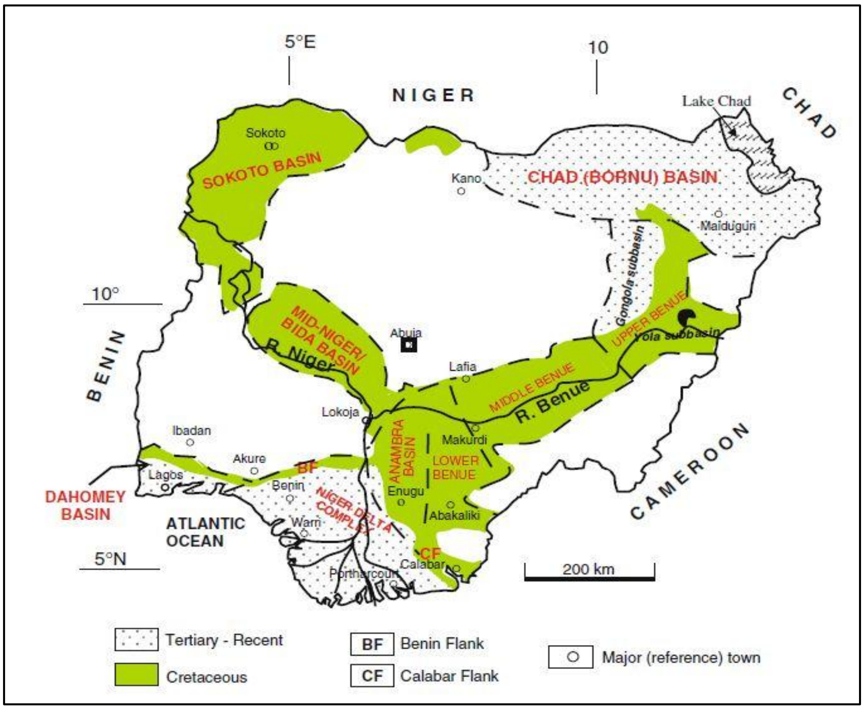


Figure 1a: Map of Nigeria showing the Benue Trough and other sedimentary Basins of Nigeria (After Obaje, 2009)

The research area lies between Latitude 9^{0} 38′ 00″ N to 9^{0} 41′ 00″ N and Longitude 12^{0} 30′ 00″ E to 12^{0} 34′ 00″ E (Figure 1b). Mulke is bordered to the north by Gombi and Hong Local Government Areas, to the east by Maiha Local Government Area, to the south by Fufore and Girei Local Government Areas, and to the west by Shelleng and Demsa Local Government Areas. It is situated approximately 70 kilometres north of Yola, the capital city of Adamawa State. It is accessible via the Yola-Girei-Dumne-Song-Gombi highway, with minor roads and footpaths leading to more remote locations.

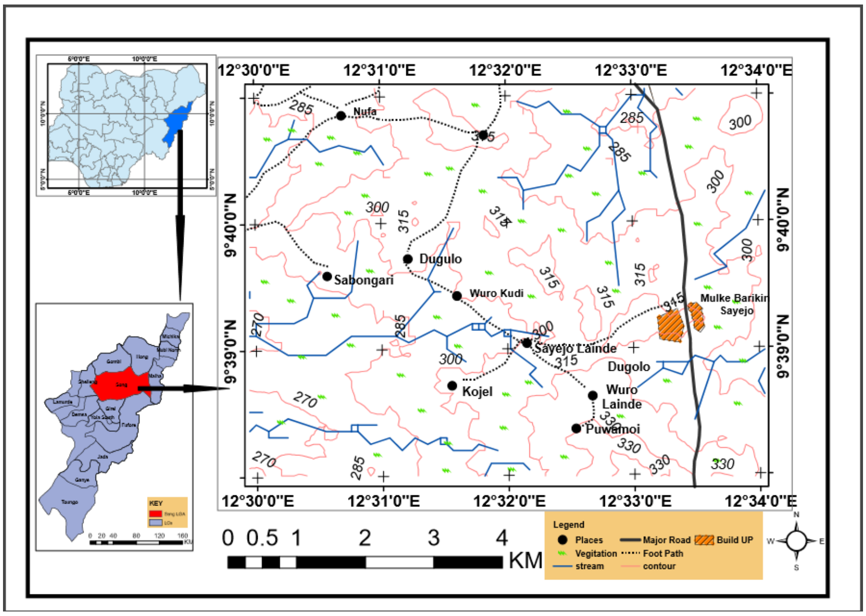


Figure 1b: Topographic Map of study area (adapted from the Federal Survey of Nigeria 1965).

MATERIALS AND METHODS

Field mapping was carried out using a handheld GPS with a scale of 1:50,000. This was done to identify outcrops, in order to systematically log them and collect fresh samples for laboratory analysis. Photographs and sketches were taken to document key sedimentary structures. A total of three (3) sections were identified, and 12 samples were collected.

The samples underwent granulometric analysis using sieving techniques, while statistical parameters were calculated based on methods proposed by Folk and Ward (1957) and Folk (1968). Grain size analysis is an essential component of sedimentary petrology, providing insights into erosion, transportation and depositional processes. The distribution of grain sizes enables the determination of transport mechanisms and sediment deposition conditions. Statistical parameters, including mean, median, kurtosis and skewness, are used to interpret these processes. However, factors such as transport distance, depositional environment, and diagenesis influence the composition of the source rock. Previous studies (Dickinson, 1985; Le Pera and Arribas, 2004; Pettijohn et al., 1987; Von Eynatten and Gaupp, 1999; Johnsson, 1993) highlight that these factors significantly alter the characteristics of the resultant sedimentary deposits. Furthermore, bivariate plots by Moiola and Weiser (1968) were used to determine the depositional environment, while Visher's (1969; 1972) log probability plots provided further insights into sedimentary processes and depositional settings. Additionally, five (5) samples were selected and used to prepare thin sections for petrographic analysis under plain polarized and cross polarized light.

RESULTS AND DISCUSSION

Geological Characteristics of the Study Area

The research area predominantly consists of the Bima Formation, which is made up of sandstone and alluvial deposits (Figure 2). These rocks have been subjected to weathering processes that contribute to soil fertility, making the region suitable for agricultural activities such as rice farming.

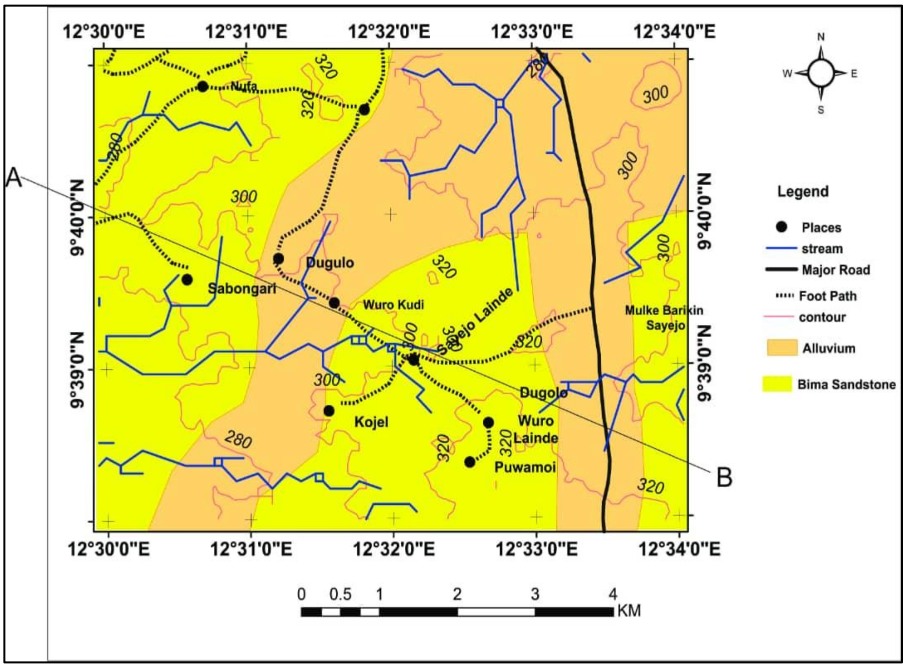
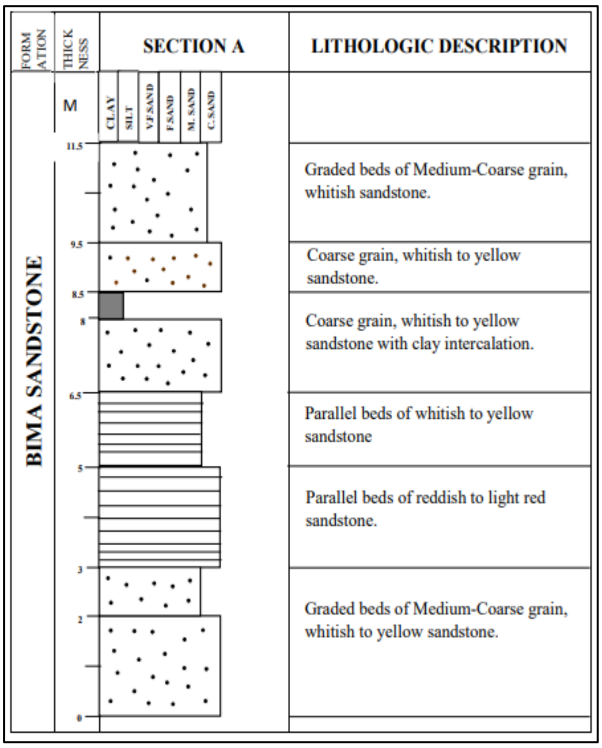


Figure 2: Geologic map of the study area



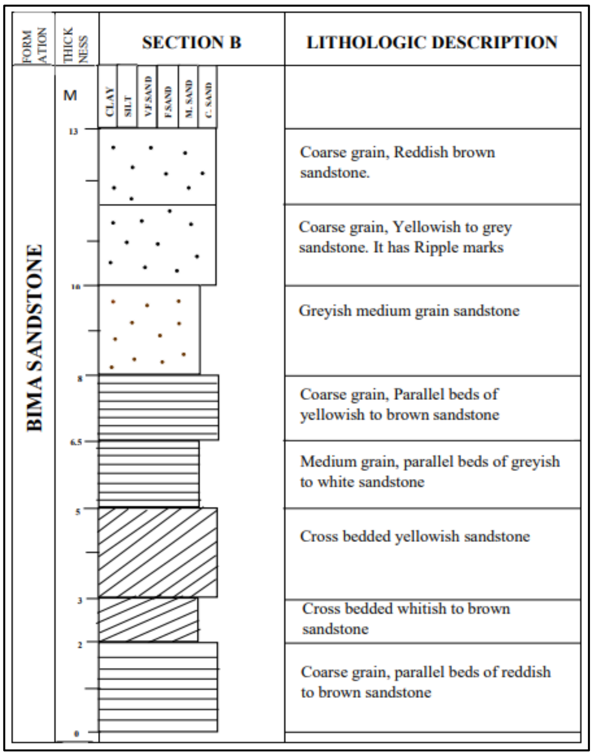


Figure 3a: Lithostratigraphic Section A

Figure 3b: Lithostratigraphic Section B

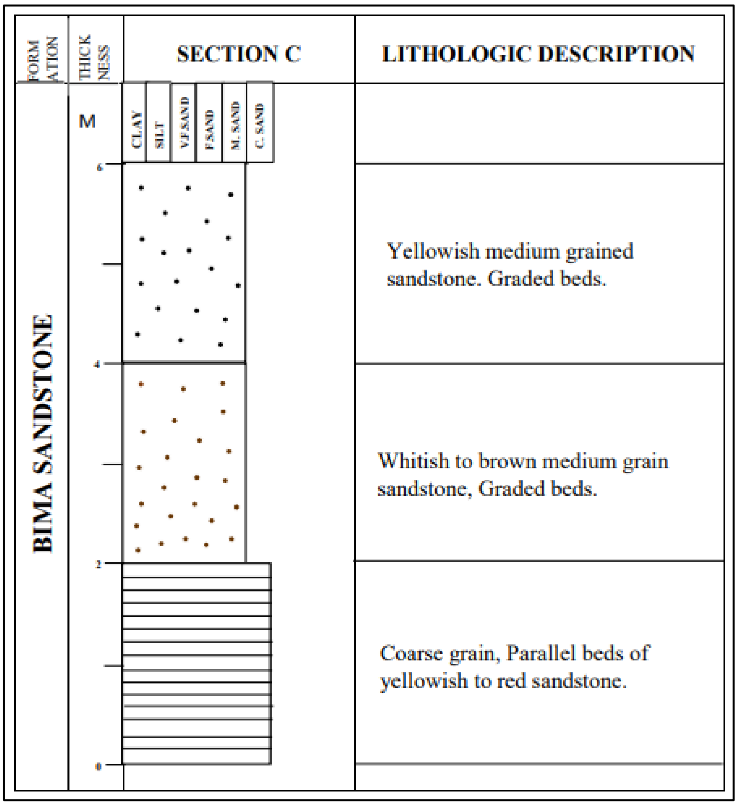


Figure 3c: Lithostratigraphic Section C

The stratigraphic sections examined above reveal a coarsening-upward sequence, indicative of fluvial deposition. Key sedimentary structures observed in the field include parallel and cross-bedding, graded bedding, massive bedding, and ripple marks (Figure 3a,3b,3c).

Petrographic Analysis

Five (5) sandstone samples were prepared for thin-section examination. The five (5) samples selected for thin-section preparation were chosen to represent the predominant lithofacies and the spatial variability noted throughout the mapped sections. These thin sections were analysed under plane-polarised light (PPL) and cross-polarised light (XPL) at 40x magnification using a petrographic microscope (Figure 4).

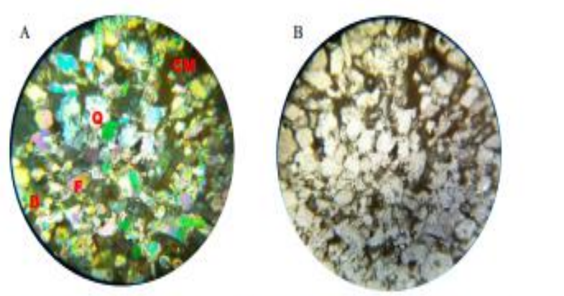


PLATE 1: (A) Under cross polarized light; (B) Under plane polarized light; Q: quartz, F: feldspar, B: biotite, CM: clay mineral (Magnification X40)

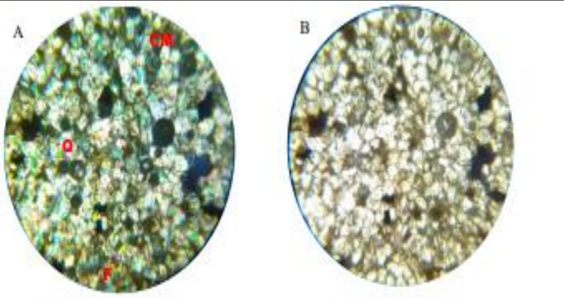


PLATE 2: (A) Under cross polarized light; (B) Under plane polarized light; Q: quartz, F: feldspar, B: biotite (Magnification X40)

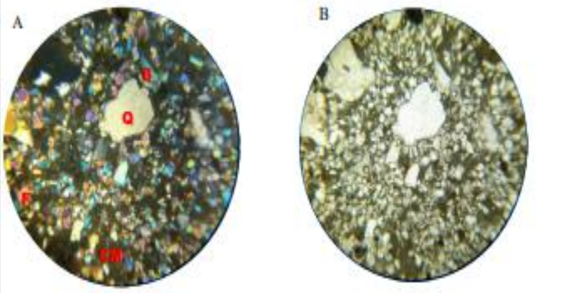


PLATE 3: (A) Under cross polarized light; (B) Under plane polarized light; Q: quartz, F: feldspar, B: biotite, CM: clay minerals. (Magnification X40)

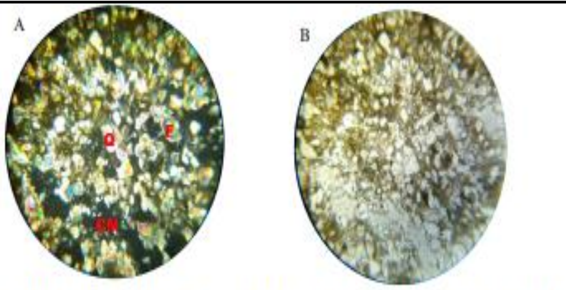


PLATE 4: (A) Under cross polarized light; (B) Under plane polarized light; Q: Quartz, F: Feldspar, CM: clay mineral. (Magnification X40)

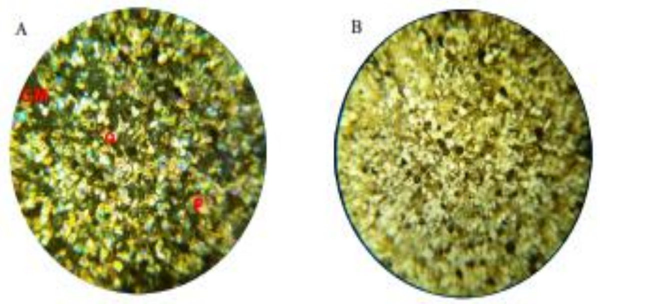


PLATE 5: (A) Under cross polarized light; (B) Under plane polarized light; Q: quartz, F: feldspar, CM: clay mineral (Magnification X40)

Figure 4: Petrographic plates

The Petrographic examination revealed that the Sandstone primarily comprises quartz (>90%), with minor feldspar and clay minerals (Figure 4). The grains exhibit angular to sub-rounded shapes with interpenetrating contacts. The sandstone is classified as quartz arenite (Pettijohn, 1973), confirming a fluvial origin.

Granulometric Analysis

Twelve (12) samples were analysed. Each was collected from different areas serving as representative samples within the study area. They sample were labelled 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12. The initial weight of each sample was 200g. To analyze grain size distribution, the percentage of each retained fraction was calculated using the formula: (weight retained / actual total weight) * 100. From these values, cumulative weight percentages were determined, which were then used to generate cumulative curves. These curves plotted cumulative weight percentage (y-axis) against the corresponding phi values (x-axis) (Figure 5 and 6). Percentile values, including Φ5, Φ16, Φ25, Φ50, Φ75, Φ84, and Φ95, were derived from the cumulative curves (Table 1). These values facilitated the computation of key textural parameters, such as mean grain size (Mz), standard deviation (σ), skewness (Ski), and kurtosis (Kc), which were instrumental in interpreting the sedimentary characteristics and depositional processes of the studied sandstone samples.

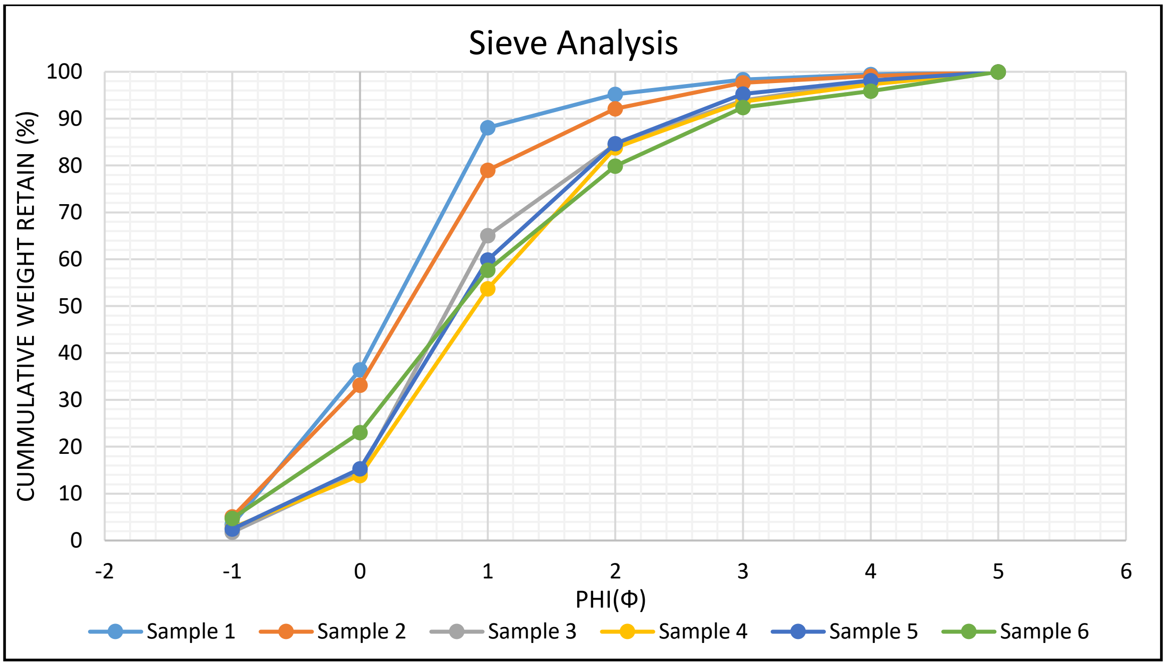


Figure 5: Cumulative frequency curve of sample 1-6

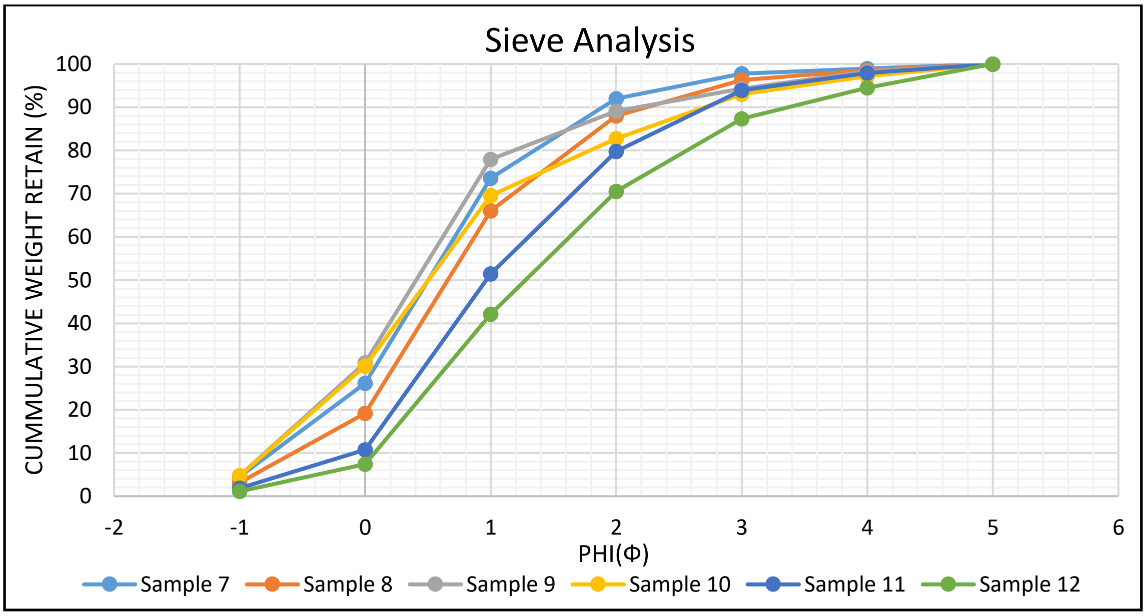


Figure 6: Cumulative frequency curve of sample 7-12

Table 1: Phi (Φ) Values Derived from the Cumulative Distribution Curve

Sample	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95
1	-0.9	-0.61	-0.35	0.25	0.77	0.9	**1.98**
2	0	-0.6	-0.3	0.4	0.9	1.38	**2.6**
3	-0.75	0.05	0.2	0.7	1.5	1.99	**3.2**
4	-0.79	0.1	0.3	0.9	1.7	2.09	**3.3**
5	-0.82	0.02	0.21	0.8	1.65	1.99	**2.98**
6	-0.97	-0.4	0.07	0.79	1.8	2.32	**3.7**
7	-0.98	-0.45	0.07	0.5	1.06	1.5	**2.43**
8	-0.9	-0.21	0.15	0.66	1.4	1.8	**2.85**
9	-1	-0.6	-0.21	0.4	0.92	1.5	**3.1**
10	-0.96	-0.58	-0.2	0.5	1.4	2.1	**3.4**
11	-0.66	0.16	0.5	0.97	2.27	2.3	**3.2**
12	-0.4	0.27	0.35	1.28	1.85	2.8	**4**

Table 2: Grain size and qualitative description of statistical parameters based on Folk and Ward (1957), and Folk (1966).

SAMPLE NO	MEAN (Mz)	STANDARD DEVIATION (σ)	SKEWNESS (Ski)	KURTOSIS (Kc)
1	0.18 Coarse Sand	0.81 Moderately Sorted	0.03 Near Symmetrical	1.05 Mesokurtic
2	0.39 Coarse Sand	0.89 Moderately Sorted	0.34 Fine Skewed	0.27 Very platykurtic
3	0.91 Coarse Sand	1.08 Poorly Sorted	0.30 Fine Skewed	1.25 Leptokurtic
4	1.03 Medium Sand	1.12 Poorly Sorted	0.18 Fine Skewed	1.20 Leptokurtic
5	0.94 Coarse Sand	1.07 Poorly Sorted	0.18 Fine Skewed	1.08 Mesokurtic
6	0.90 Coarse Sand	1.39 Poorly Sorted	0.19 Fine Skewed	1.11 Mesokurtic
7	-0.48 Very Coarse Sand	1.00 Moderately Sorted	0.08 Near Symmetrical	1.41 Leptokurtic
8	0.75 Coarse Sand	1.07 Poorly Sorted	0.15 Fine Skewed	1.23 Leptokurtic
9	0.43 Coarse Sand	1.15 Poorly Sorted	0.18 Fine Skewed	1.49 Leptokurtic
10	0.67 Coarse Sand	1.33 Poorly Sorted	0.26 Fine Skewed	1.12 Leptokurtic
11	1.14 Medium Sand	1.12 Poorly Sorted	0.20 Fine Skewed	1.05 Mesokurtic
12	1.45 Medium Sand	1.30 Poorly Sorted	0.22 Fine Skewed	1.02 Mesokurtic
	Mean	Sorting	Skewness	Kurtosis
Minimum	-0.48	0.81	0.03	0.27
Maximum	1.45	1.39	0.34	1.49

Depositional Environment

Univariate Analysis

The grain size parameters were examined using both univariate and bivariate analyses. The univariate approach focused on individual parameters (Table 2). Mean grain size, which represents the central tendency, provides insight into the average size of sediment particles. In sedimentary environments, it reflects the kinetic energy or velocity of the depositing medium (Sahu, 1964). The analysed sediment samples had mean grain sizes ranging from -0.48 to 1.45Φ, classifying them as coarse to medium sands. Standard deviation measures sorting and indicates variations in the depositional energy of the transporting medium.

Sorting values ranged from 0.81 to 1.39, suggesting that the sands exhibit moderate to poor sorting. Skewness evaluates the asymmetry of the grain size distribution and the relationship between the mean and median. Skewness values varied from 0.03 to 0.34, indicating nearly symmetrical to fine-skewed distributions. Kurtosis, which assesses the sharpness of the grain size distribution curve, ranged from 0.27 to 1.49. This variation classified the sands as very platykurtic to leptokurtic. Although kurtosis is traditionally used to measure peakness, Kendall and Stuart (1958) argue that it should instead be viewed as a sorting ratio rather than a descriptor of curve shape. A normal distribution has a kurtosis of one, while values exceeding unity suggest restricted velocity fluctuations within the central 50% of average flow conditions. The examined samples were predominantly mesokurtic on average, further affirming their fluvial depositional origin.

Bivariate Analysis

Bivariate analysis was employed to assess depositional conditions using multiple statistical parameters. A widely recognized approach, first utilized by Moiola and Weiser (1968), involves plotting sorting values against skewness to distinguish depositional environments. The resulting plot indicates that the studied sediments align closely with river sands. This indicates that the sediments have undergone some degree of transportation while retaining characteristics of their source material (Figure 7). Additionally, a cross-plot of sorting against mean grain size (Figure 8) reveals a clustering pattern for most samples, with exceptions noted in samples 1, 2, and 7, suggesting variability in depositional energy and transport processes.

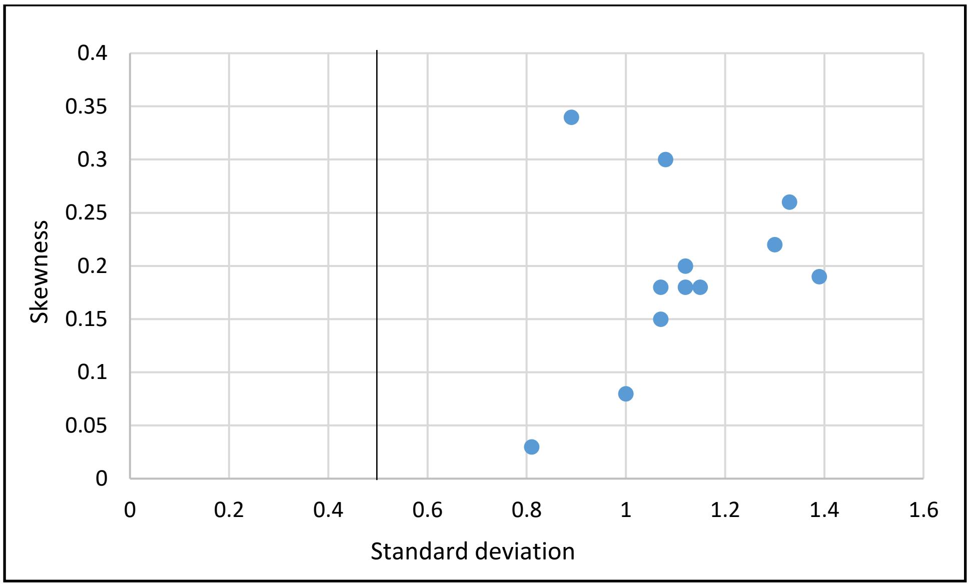


Figure 7: A bivariate plot illustrating the relationship between standard deviation (sorting) and skewness, adapted from Moiola and Weiser (1968).

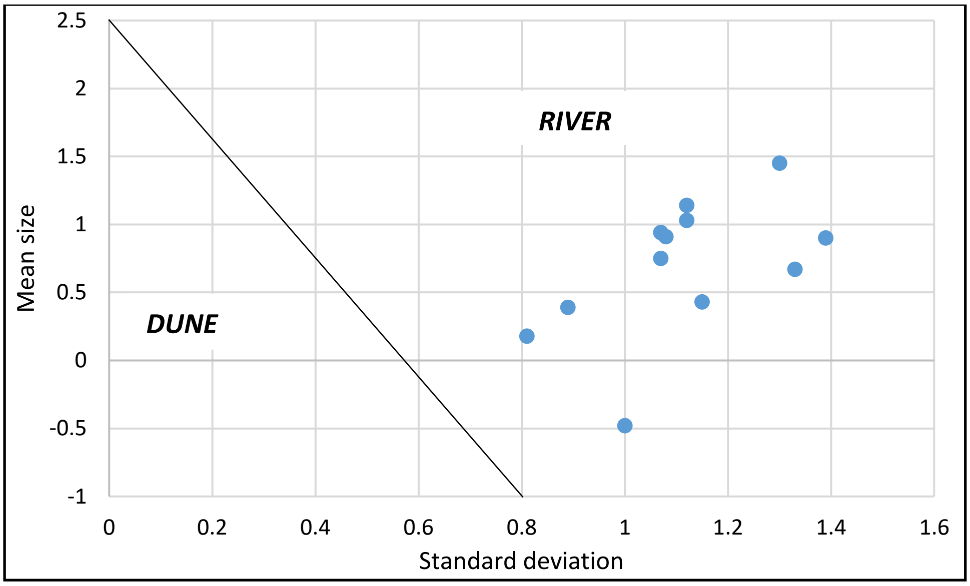


Figure 8: A bivariate plot illustrating the relationship between standard deviation (sorting) and mean, adapted from Moiola and Weiser (1968).

The clustering of data points within the river sand field suggests fluvial processes played a dominant role in sediment deposition (Figure 8). The similarity in deposition mechanisms across all samples is evident from their clustering within the same field on the bivariate plots. The data confirm that all analyzed samples align with the river sand classification, reinforcing the univariate analysis findings that indicate a fluvial depositional environment.

From the analysis, the sediments in the study area are best described as medium to coarse-grained, poorly sorted, near-symmetrical mesokurtic sands. These characteristics align with typical river sands, suggesting deposition in a high-energy fluvial environment. The moderate to poor sorting indicates limited sorting during deposition within a fluvial setting. Additionally, bivariate scatter plots by Moiola and Weiser (1968) further support the fluvial origin, as all samples fall within the river field. Combining statistical, graphical, and sedimentary structure analyses, it is evident that the sandstone deposits in Mulke were formed in a fluvial environment. The granulometric features and depositional interpretation of the Bima Sandstone in this study align with earlier research from the Northern Benue Trough. Similar medium- to coarse-grained, poorly sorted sandstones indicative of fluvial deposition have been reported by Mustapha et al. (2019), Finthan and Mamman (2020), and Finthan et al. (2022). Furthermore, Amodu et al. (2023) documented comparable grain-size parameters and facies associations in the Yola Sub-basin, interpreting the Bima Sandstone as of fluvial origin. These parallels imply that fluvial processes predominantly influenced the deposition of the Bima Sandstone across the Northern Benue Trough.

Comparisons between grain size distributions from differing environments using log probability plots have been reported by Visher (1969; 1972) and this shows systematic differences. The plot below shows straight-line segments representing creep, saltation and suspension (Figure 9).

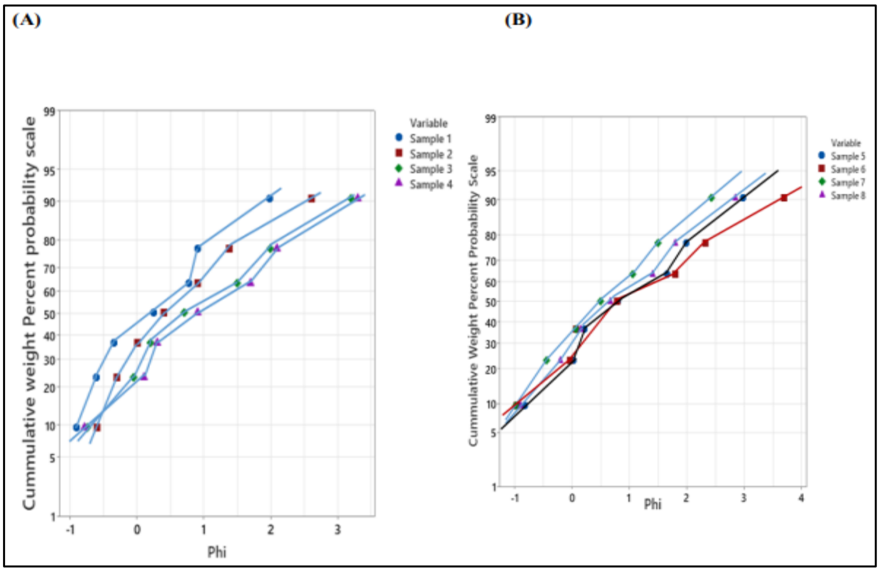


Figure 9: Log probability plots illustrating the distribution of Bima Sandstone samples. (A) Probability plot for Sample 1-4; (B) probability plot for sample 5-8).

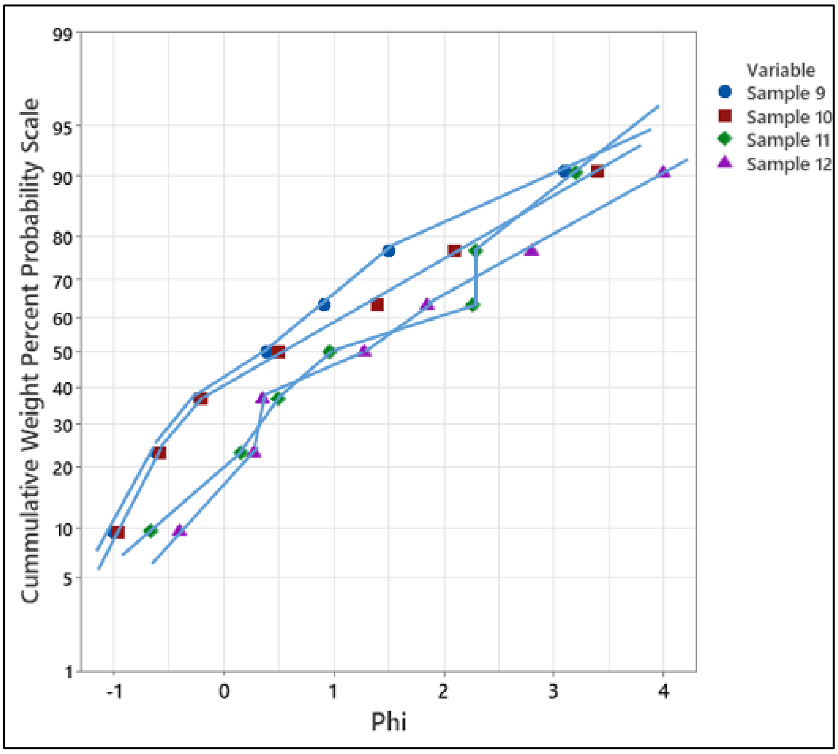


Figure 10: Log probability plots illustrating the distribution of Bima Sandstone samples (Samples 9-12)

Moss (1962; 1963) proposed that sediment transport occurs through surface creep, saltation, and suspension, each contributing distinct modes in grain size distributions. Analysis of the study area samples revealed three primary sedimentary populations, although the majority exhibited two dominant populations (Figures 9 and 10). This observation aligns with characteristics of fluvial sands reported by Visher (1969, 1972), Amaral and Pryor (1977) and recent sedimentological studies of the Bima Sandstone in the Northern Benue Trough (Mustapha et al., 2019; Finthan and Mamman, 2020; Finthan et al., 2022; Amodu et al., 2023), further supporting the interpretation of a fluvial depositional environment.

The fluvial characteristics of the Bima Sandstone, which is medium to coarse-grained, imply a potential for groundwater storage in areas where porosity is maintained or improved. Furthermore, the prevalence of coarse sand and gravelly facies points to the unit's appropriateness as a source for construction and aggregate materials.

CONCLUSION

This study integrated field mapping, granulometric, and petrographic analyses to evaluate the geological characteristics of the study area. A geological map was produced, and 12 representative samples were collected for both granulometric and petrographic assessments. Sedimentary structures such as parallel beds, cross-bedding, massive bedding, graded bedding, and ripple marks were observed in the field.

Grain size analysis revealed that the sandstone consists of very coarse to medium sand. The sorting values, which ranged from moderate to poor, align with characteristics typical of fluvial sands. The studied samples exhibited near-symmetrical to fine-skewed distributions and ranged from very platykurtic to leptokurtic. The depositional environment, determined through bivariate analysis, confirms that the formation was deposited under fluvial conditions. Based on the collected data, it can be concluded that the study area represents a fluvial depositional environment.

ACKNOWLEDGEMENT

The authors are grateful to the Department of Geology, Modibbo Adama University, Yola, for providing the facilities and institutional support for this study. We also appreciate the assistance of laboratory staff and local guides during fieldwork and sample analysis. The constructive contributions of colleagues who reviewed the manuscript are gratefully acknowledged.

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