Facies Analysis and Grain Size Distribution of the Bima Formation: Insights into the Depositional Environment in Yarandua and Dadinkowa, Gongola Sub-Basin, Northern Benue Trough

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Abstract
This study provides a comprehensive facies and granulometric analysis of the Cretaceous Bima Formation in the Yarandua and Dadinkowa areas of the Gongola Sub-Basin in Northeastern Nigeria. The study aimed at interpreting the depositional environments and enhance our understanding of the sedimentary processes that influenced this stratigraphic unit. Three lithostratigraphic sections, the Yarandua Quarry, Eastern Yarandua, and Dadin Kowa sections—were analyzed. Fieldwork involved sedimentary logging, describing lithofacies, measuring paleocurrent, and collecting twenty-nine sandstone samples for laboratory analysis. Grain size distribution was determined using dry mechanical sieving, and statistical parameters were calculated using the Folk and Ward graphical method. These parameters included mean grain size, sorting, skewness, and kurtosis, which helped interpret the energy conditions and transport mechanisms of the depositional system. The identified facies include matrix-supported conglomerates, cross-bedded coarse to very coarse sandstones, as well as interbedded fine-grained mudstone and siltstone units. These facies indicate deposition within a progradational alluvial fan transitioning to a braided river system. Vertical facies transitions suggest a gradual decrease in depositional energy from the base to the top of the formation. The grain size results reveal a predominance of coarse-grained, poorly sorted, and positively skewed sediments, indicating deposition under fluctuating, high-energy flow conditions. The combined findings from fieldwork and laboratory analysis suggest that the Bima Formation was deposited in a high-energy fluvial environment, characterized by sediment gravity flows and braided channel processes.

***Keywords**: Bima Formation, Facies analysis, Grain size distribution, Alluvial fan, Braided River, Depositional environment, Northern Benue Trough, Gongola Sub-Basin*

INTRODUCTION

Several lines of evidence indicate that the Benue Trough is part of the larger West and Central African Rift System basins, which formed due to the separation of the African and South American plates during the Jurassic period (Guiraud, 1992; Guiraud *et al.*, 2005; Genik *et al.*, 2013). The Benue trough is geographically divided into Southern, Central, and Northern portions (Nwajide, 2013)(Fig: 1). The Northern Benue Trough is further subdivided into three basins: the east-west trending Yola Basin (Yola Arm), the north-south trending Gongola Basin (Gongola Arm), and the northeast-southwest trending Lau Basin (Main Arm) (Guiraud, 1990; Dike, 2002).

The Gongola basin consists of a stratigraphic succession that includes the Aptian-Albian Continental Bima Formation, the Cenomanian transitional-marine Yolde Formation, the Cenomanian-Santonian marine Pindiga Formation, the Campano-Maastrichtian Deltaic Gombe Formation, and the Tertiary Continental Keri-Keri Formation (Tukur *et al.*, 2015)(Fig: 2).). The Aptian-Albian syn-rift to post-rift fluvial and lacustrine successions of the continental Bima Formation unconformably overlie the Basement Complex Rocks (Guiraud, 1990; Tukur *et al.*, 2015; Samaila, 2008; Shettima *et al.*, 2018), which constitute the oldest sedimentary unit. Guiraud (1990) provided the most detailed accounts of the Bima Sandstone, describing its three subdivisions, Bima 1, Bima 2, and Bima 3, and elevating its status to that of a group.

In addition to the Chad (Bornu) Basin and other inland basins within Nigeria, commercial hydrocarbon reserves have been found in other segments of the rift trend located in nearby countries such as Chad (Doba, Doseo, and Bongor fields), Niger (Termit-Agadem Basin), and Sudan (Muglad Basin), which share genetic relationships and similar structural characteristics (Mohammed *et al.* 1999; Obaje *et al.* 2004). They note that the primary source rocks and reservoirs found in the Muglad Basin are within the Aptian-Albian-Cenomanian continental deposits of the Abu Gabra and Bentiu Formations, respectively Obaje (2004). These formations are comparable and can be correlated with the well-established Bima Formation found in the Nigerian section of the Chad Basin and the Upper Benue Trough.

While significant research has been conducted on the Bima Formation, particularly concerning its hydrocarbon potential, notable gaps hinder a comprehensive understanding of its reservoir quality, especially in the Yarandua and Dadinkowa areas.

Moreover, while researchers such as Nabage *et al.* (2024) have examined diagenetic processes, their work does not adequately address how these alterations specifically impact the reservoir quality of the Bima Formation in Yarandua and Dadinkowa. Furthermore, limited research has been conducted on facies variations within the Bima Formation, which could reveal significant depositional environments and their implications for reservoir characteristics (Shettima *et al.*, 2018). Addressing these gaps is essential for enhancing our understanding of this vital resource and improving regional exploration strategies.

This research integrates lithostratigraphic logging and laboratory analysis, including sedimentological (grain size distribution) of the three lithostratigraphic sections of the Bima Formation in the Yarandua and Dadinkowa areas of Northeastern Nigeria, in order provide detail sedimentological information and impetus for understanding the petroleum system potentials of the Bima Formation in the area.

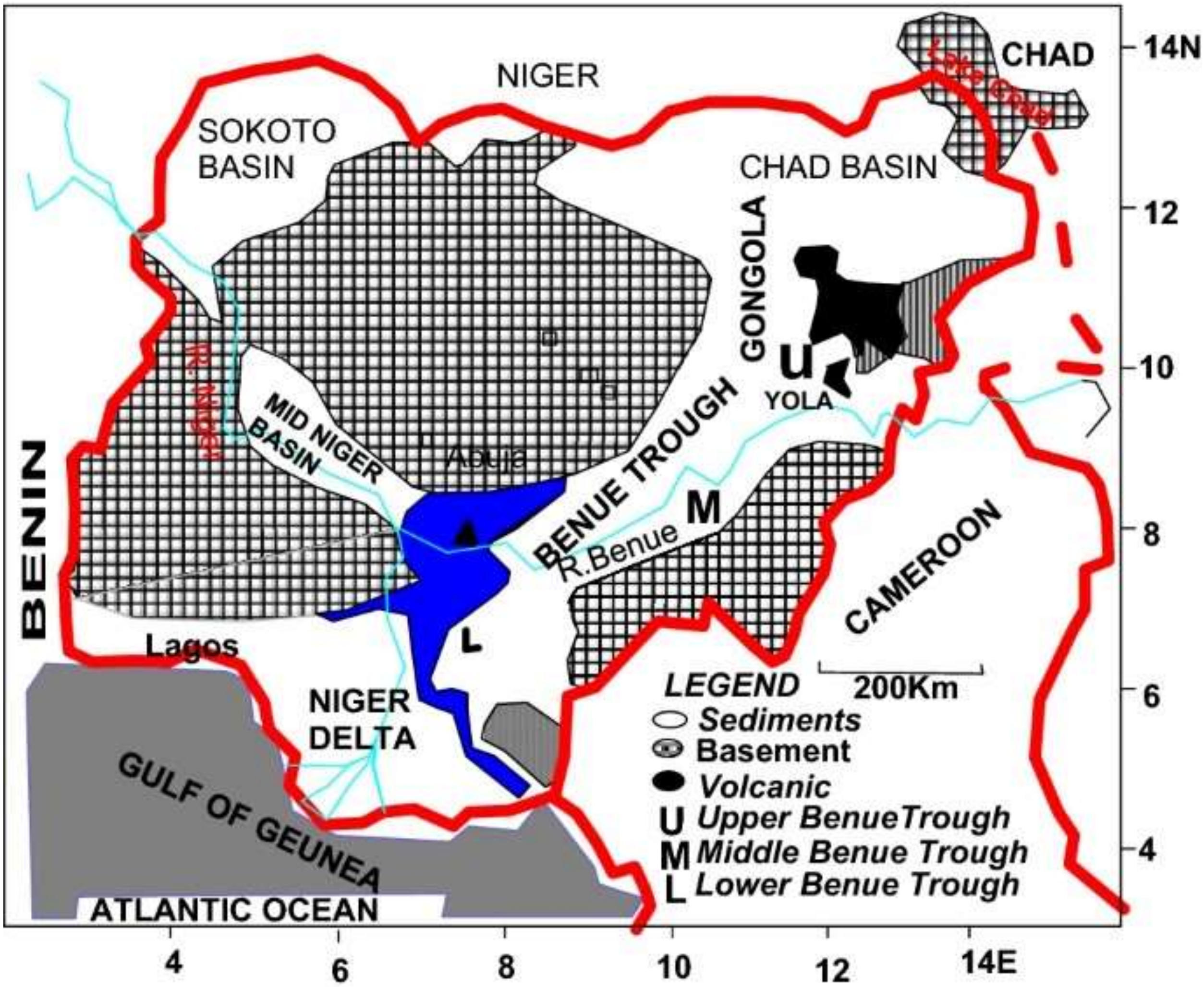

Fig. 1: Geological map of Nigeria showing the Benue Trough (Jauro et al., 2007; as modified by Akinyemi et al., 2023).

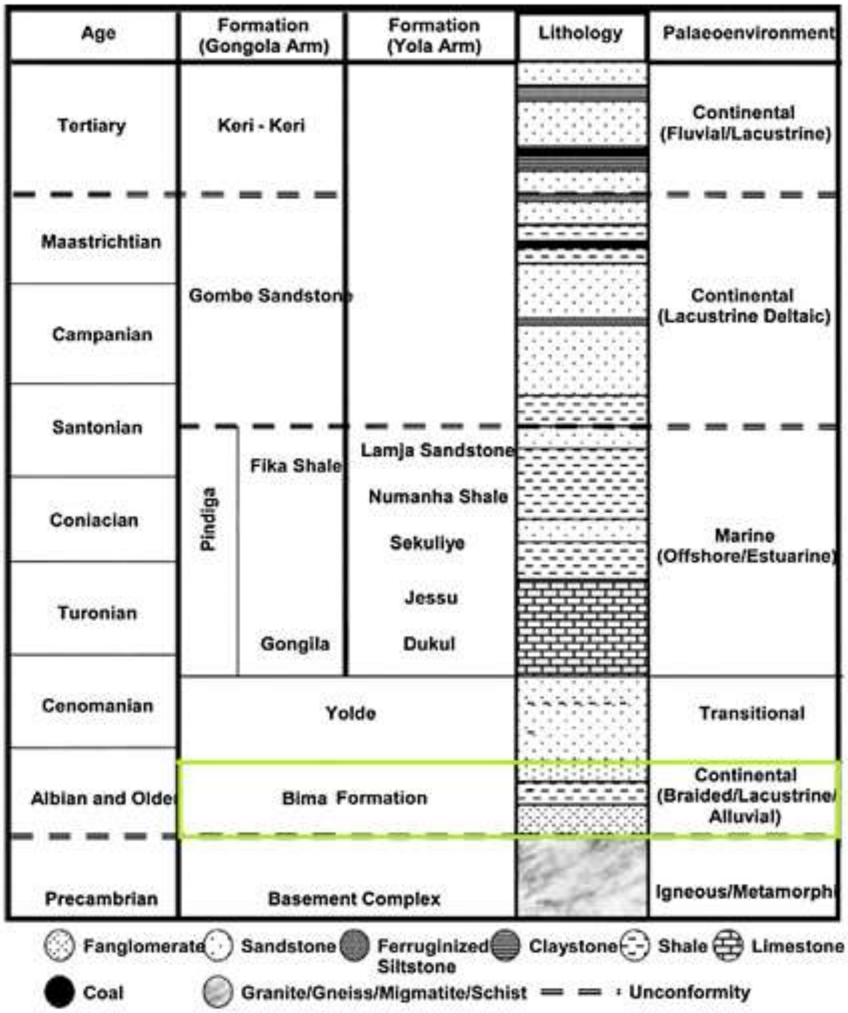

Fig. 2: Stratigraphic sequence of the Northern Benue Trough, Nigeria (modified from Abubakar, 2006; Sarki Yandoka et al., 2014).

METHODOLOGY

The three lithostratigraphic sections observed in this research were located within the Yarandua (Latitude 10^0 21' 43'', Longitude 11^0 32' 44'' and Latitude 10^0 21'56'', Longitude 11^0 32' 46''), and Dadin Kowa (Latitude: 10^0 17' 25'' and Longitude: 11^0 29' 4''), Yamaltu/Deba Local Government Area of Gombe State, North-eastern Nigeria (Fig. 3). This area is part of the Gongola Sub-basin, which is a significant component of the Upper Benue Trough. Geographically, the Yarandua and Dadinkowa areas are positioned southeast of Gombe City. The areas are accessible through the Gombe and Biu roads, respectively.

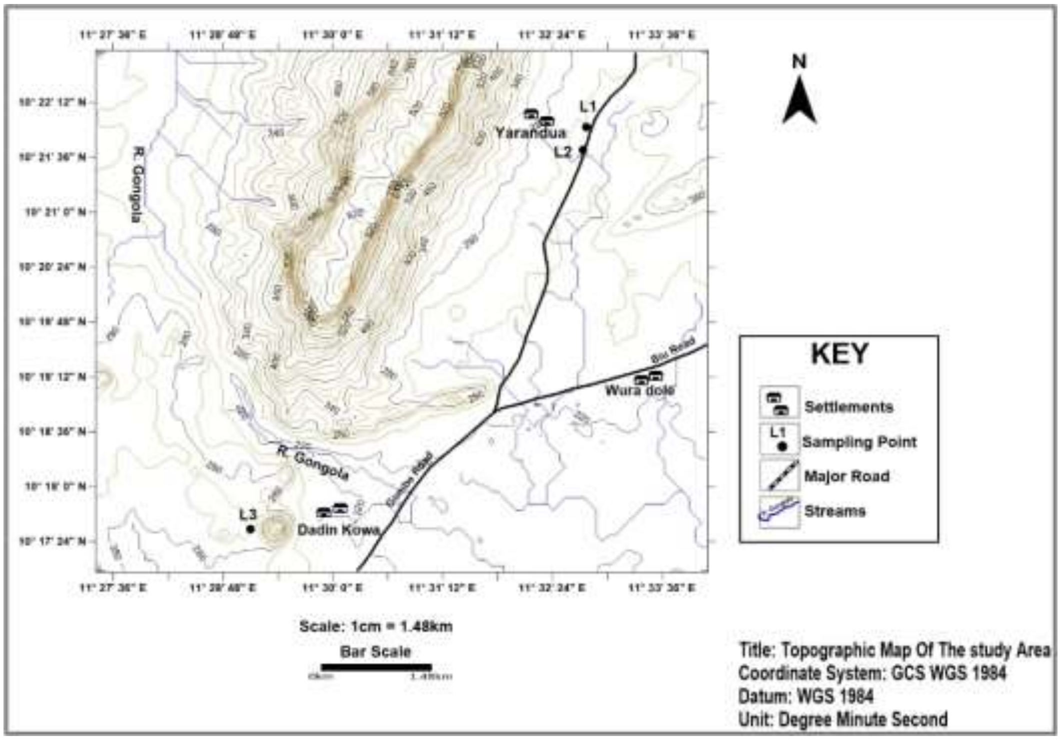

Fig. 3: Map of the Study Area

Fieldwork and Sample Collection

The fieldwork for this research was carried out on the exposed two litho-sections of the Yarandua and one litho-section of the Dadin Kowa areas of Northeastern Nigeria. The coordinates of each location were recorded using the Global Positioning System (GPS). Data on the thickness of beds, lithology, colour, paleocurrent direction, grain size, and sedimentary structures were systematically observed and recorded on a lithologic log.

Different beds were identified based on changes in grain size and colour. The thickness of beds was measured using a measuring tape. The paleocurrent direction was determined by measuring the direction of the trough crossbedding using a compass clinometer. This process involved aligning the sight vane with the sedimentary structure and accurately recording the bearing. Representative rock samples from each bed were taken using a hammer and labeled with masking tape and a marker pen. The data on the litho-log were further plotted and analyzed using Sed log 3.0 software to classify the rocks into different facies.

Laboratory work

Twenty-nine (29) sandstone samples were collected from the three lithologic sections of the Bima Formation for granulometric analysis at the geology laboratory of Abubakar Tafawa Balewa University, Bauchi.

The granulometric analysis was performed using the standard dry mechanical sieving method outlined in ASTM D422-63(2007), the Standard Test Method for Particle-Size Analysis of Soils. Before the analysis, uniform particle distribution was achieved by carefully disaggregating samples with a mortar and pestle.

Approximately 200 grams of each representative sample were weighed and placed in the top sieve of a series of stainless-steel sieves arranged in descending mesh sizes: 2.00 mm, 1.40 mm, 1.00

mm, 0.71 mm, 0.50 mm, 0.25 mm, 0.15 mm, 0.09 mm, and 0.063 mm. This sieve stack was securely positioned on an Endecott's mechanical sieve shaker and operated for 10 minutes to promote size-based particle separation.

The material collected on each sieve was carefully weighed with a digital balance following the sieving process. The weight of particles retained at each sieve interval was recorded, enabling the determination of grain size distribution and the computation of statistical parameters such as mean grain size, sorting, and skewness.

Grain size distribution was analyzed using sieve analysis data, calculating cumulative weight percent retained by adding percentages from each sieve, starting with the coarsest. These percentages were plotted against grain diameters to create cumulative grain size distribution curves, following Folk's 1957 method.

Microsoft Excel was used to plot the cumulative curves' graph and derive statistical grain size parameters using the graphical method introduced by Folk and Ward (1957, 1970). The primary parameters calculated include:

a. Graphic Mean (M_Z): Represents the average grain size, calculated using the formula:

$$M_Z = \frac{\emptyset_{16}+\emptyset_{50}+\emptyset_{84}}{3}$$ (Folk & Ward, 1970)

b. Inclusive Graphical Standard Deviation (**M_Z**)**:** Indicates sorting or the spread of grain sizes within each of the samples, calculated as; $\delta_i = \frac{\emptyset_{84}-\emptyset_{16}}{4} + \frac{\emptyset_{95}-\emptyset_{5}}{6.6}$ (Folk and Ward (1970).

c. Inclusive Graphic Skewness (SK_I): Measures the asymmetry grain size distribution curve, calculated using $SK_t = \frac{(\emptyset_{84}+\emptyset_{16}-2\emptyset_{50})}{2(\emptyset_{84}-2\emptyset_{16})} + \frac{\emptyset_{95}+\emptyset_{5}-2\emptyset_{50})}{2(\emptyset_{95}-\emptyset_{5})}$ (Folk and Ward (1970)

Results and Discussion

Lithostratigraphy

Three lithologic sections of the Bima Formation were studied, two located in Yarandua town (the Quarry section and the Western Yarandua section) and one in Dadin Kowa (the Dadinkowa section). The two sections exposed around Yarandua show distinct thicknesses of 27 m and 10 m, while the section at Dadin Kowa has a thickness of 21 m.

Facies Description

The Yarandua Quarry Section

This section (Fig. 4) has five (5) basic facies: MSCPF facies (Matrix-supported conglomerate), PCMSF facies (Intercalated, Purple-Colored Mudstone and Silt), PCMFF facies (Intercalated, Purple-Colored Mudstone with Fine-Grained Sand), CVTF facies (Coarse to Very Coarse-grained Trough Cross-Bedded sandstone), and MCTMF facies (Medium-to Coarse-grained Trough Cross-bedded Sandstone with Mudstone Lenses).

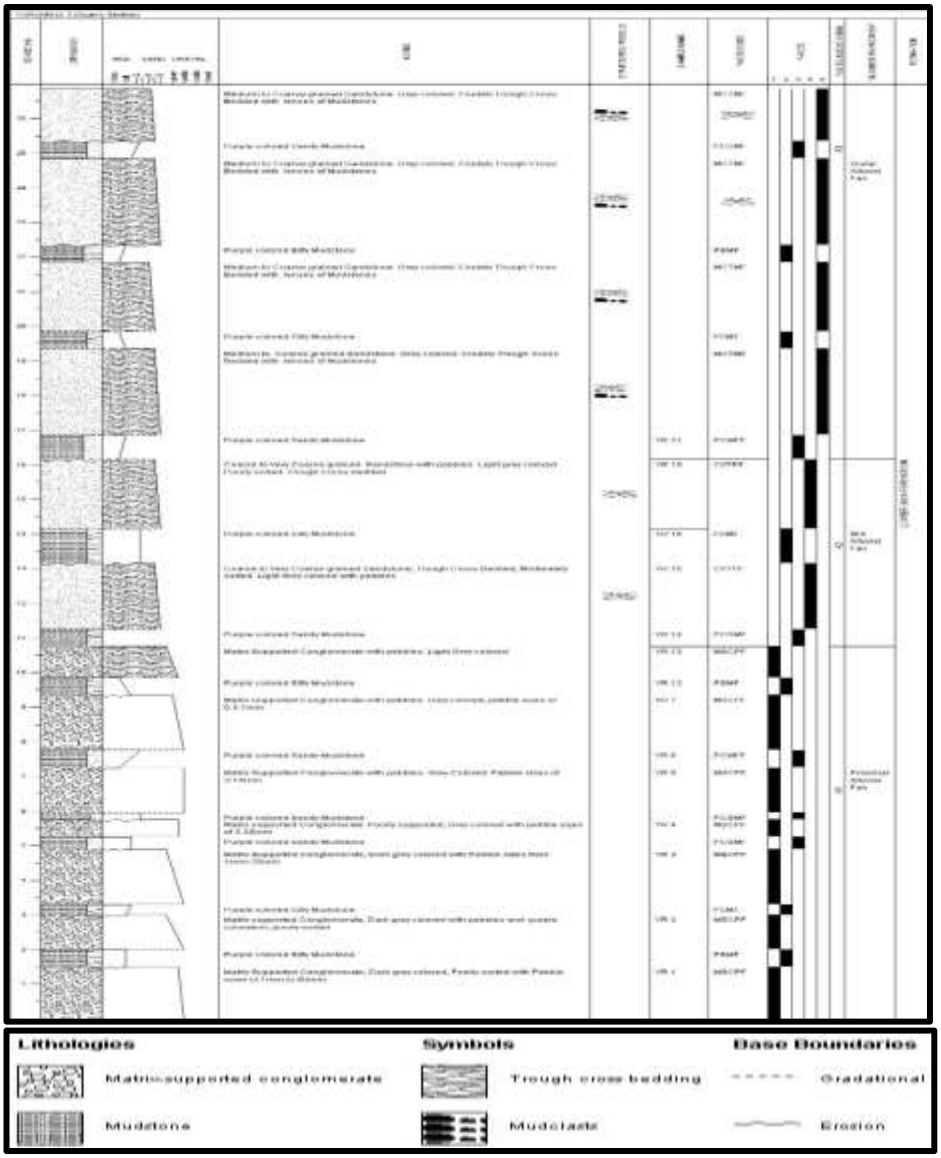

Fig. 4: Lithostratigraphic Quarry section at Yarandua with description of lithologies and Granulometric sample points

intercalated, purple-colored mudstone with silt having a thickness of approximately 0.5 meters (Fig. 5 b). The PCMFF is composed of fine-grained, purple-colored sand and is divided into three distinct units. The first two units, measuring 35 cm and 50 cm thick, overlie the MSCPF facies with erosional contacts (Fig. 5c). The CVTF facies is a light grey sedimentary unit distinguished by its trough crossbedding and the presence of pebbles with a total thickness of 3.9 meters (Fig. 5d). The MCTMF facies is characterized by a medium- to coarse-grained sandstone exhibiting crude trough crossbedding having lenses of mudstone with a total thickness of 4.0 meters.

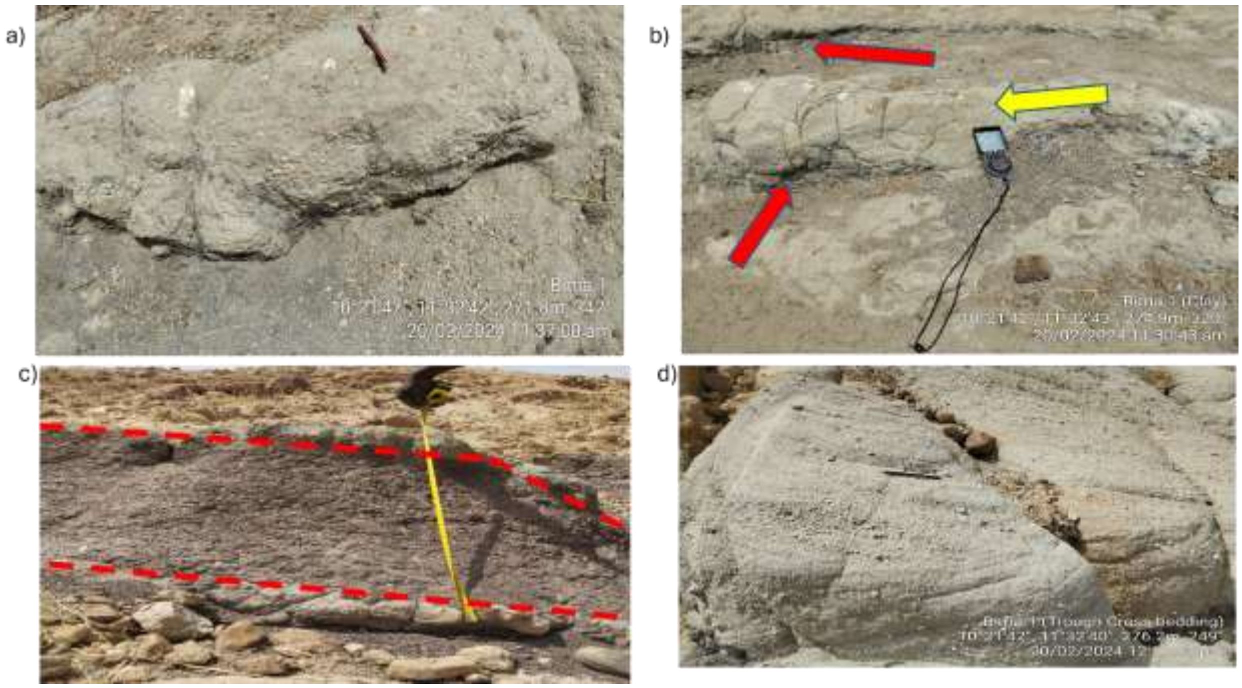

Fig. 5: Facies of the Yarandua section 1: a) MSCPF: Matrix Supported Conglomerate, b) PCMSF: Intercalated Purple Colored Mudstone and Silt, c) PCMFF: Intercalated Purple Colored Mudstone with Fine-Grained Sand, d) MCTMF: Medium to Coarse-grained trough cross-bedded Sandstone with mudstone lenses

The Yarandua 3 Quarry Section showcases a progradational alluvial fan sequence, transitioning from proximal debris-flow deposits (MSCPF) to mid-fan braided channel facies (CVTPF, MCTMF), and finally to distal overbank/floodplain deposits (PSMF, PCMSF). This vertical facies arrangement is characteristic of coalescing fan systems influenced by episodic high-energy flows and sediment gravity processes (Miall, 1977; Rust, 1978; Collinson, 2002; Amodu et al., 2023). The upward decrease in energy illustrates a classical alluvial fan to braided stream transition commonly seen in the Lower Cretaceous fluvial systems of the Upper Benue Trough (Guiraud, 1990; Finthan & Mamman, 2020).

The Eastern Yarandua Section (10 m thick)

This section (Fig. 6) is characterized by VCTF Facies (Very coarse to coarse pebbly Sandstone), MCTF Facies (Medium to Coarse-grained Trough Cross bedded sandstone) and VTF Facies (Very Coarse-grained Sandstone)

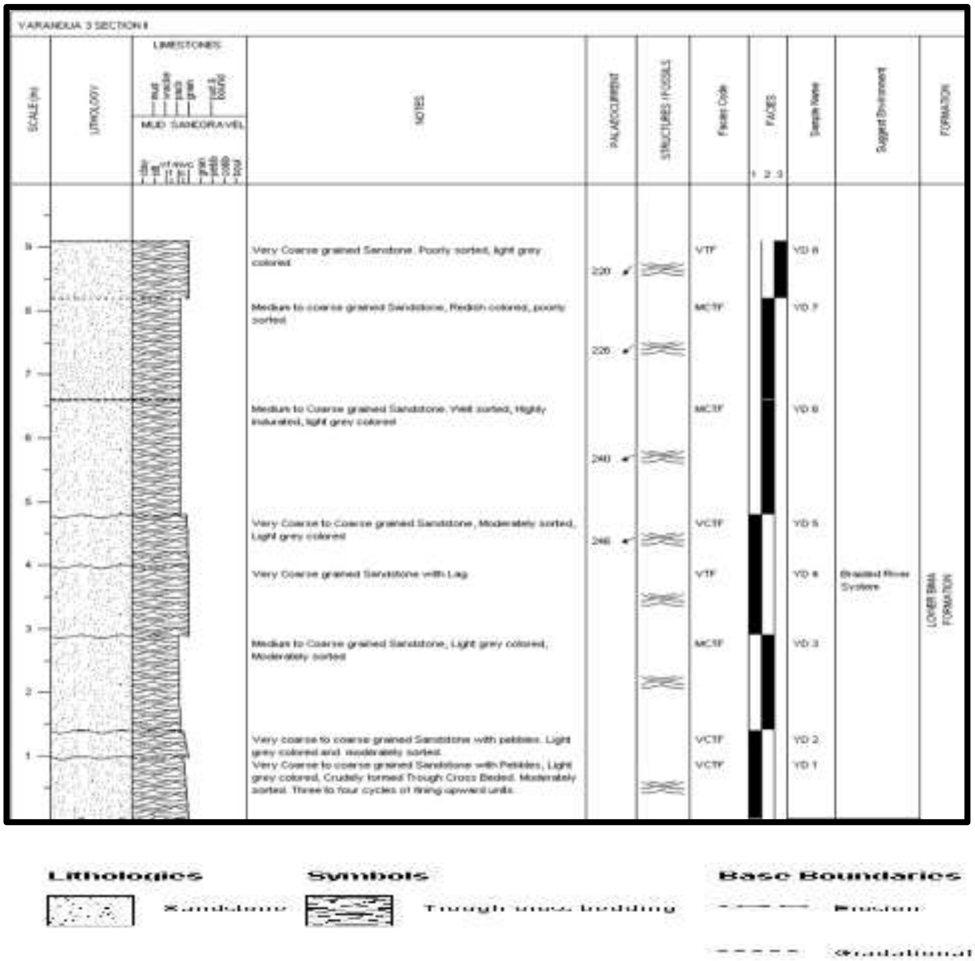

Fig. 6: Lithostratigraphic section of the Eastern Yarandua with description of lithologies, Granulometric sample points

The VCTF Facies is characterized by light gray, moderately sorted sandstone with very coarse to coarse grain sizes, displaying crude trough crossbedding with a paleocurrent direction of 246°. The total thickness of the facies is 2.2 meters. *The MCTF Facies* is characterized by light gray, moderately sorted, medium to coarse-grained sandstone with a total thickness of 4.8 meters and a paleo-current direction of 226^0. The *VTF Facies is* characterized by light grey, poorly sorted, very coarse-grained sandstone with a total thickness of 1.7 m.

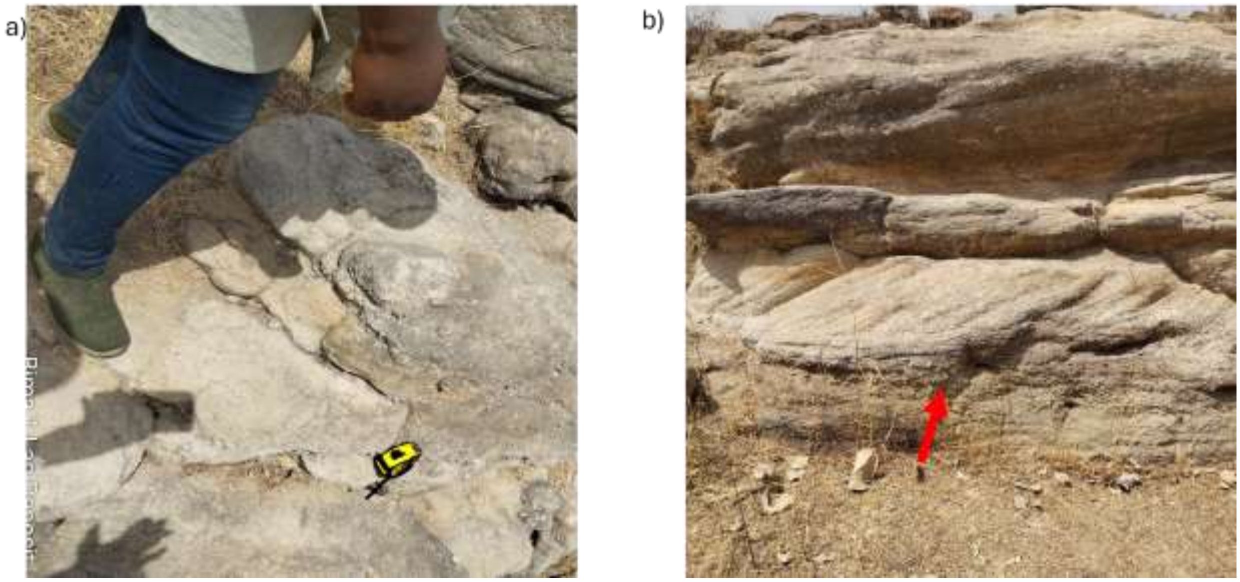

Fig. 7: Facies of the Eastern Yarandua section: a) MCTF: Medium to coarse-grained trough Cross - bedded sandstone (b) VCTF: Very coarse to coarse trough cross-bedded sandstone

The Eastern Yarandua Section is a high-energy braided fluvial environment, marked by the prevalence of coarse to very coarse-grained sandstones with trough cross-bedding and clear paleocurrent directions (246° and 226°). The VCTF and MCTF facies are seen as migrating bar deposits within active braided river channels, featuring bedload-dominated sediment transport and moderate sorting (Miall, 2010; Moiola & Weiser, 1968; Amodu et al., 2023). The VTF facies, being massive and poorly sorted, probably represents deposition from flash floods or sheet floods linked to sudden energy fluctuations. This interpretation fits with sediment gravity flow conditions in proximal braided systems, where high discharge rapidly deposits coarse material with minimal sorting (Sahu, 1964; Miall, 1996; Amodu et al., 2023).

The Dadinkowa Stratigraphic Section

This section (Fig. 8) is characterized by MCTF facies *(*Medium to coarse-grained trough cross-bedded sandstone), the CSTF facies (Coarse-grained trough cross-bedded sandstone), and the CVTF facies (Coarse to very coarse-grained sandstone) with a total thickness of 21 m.

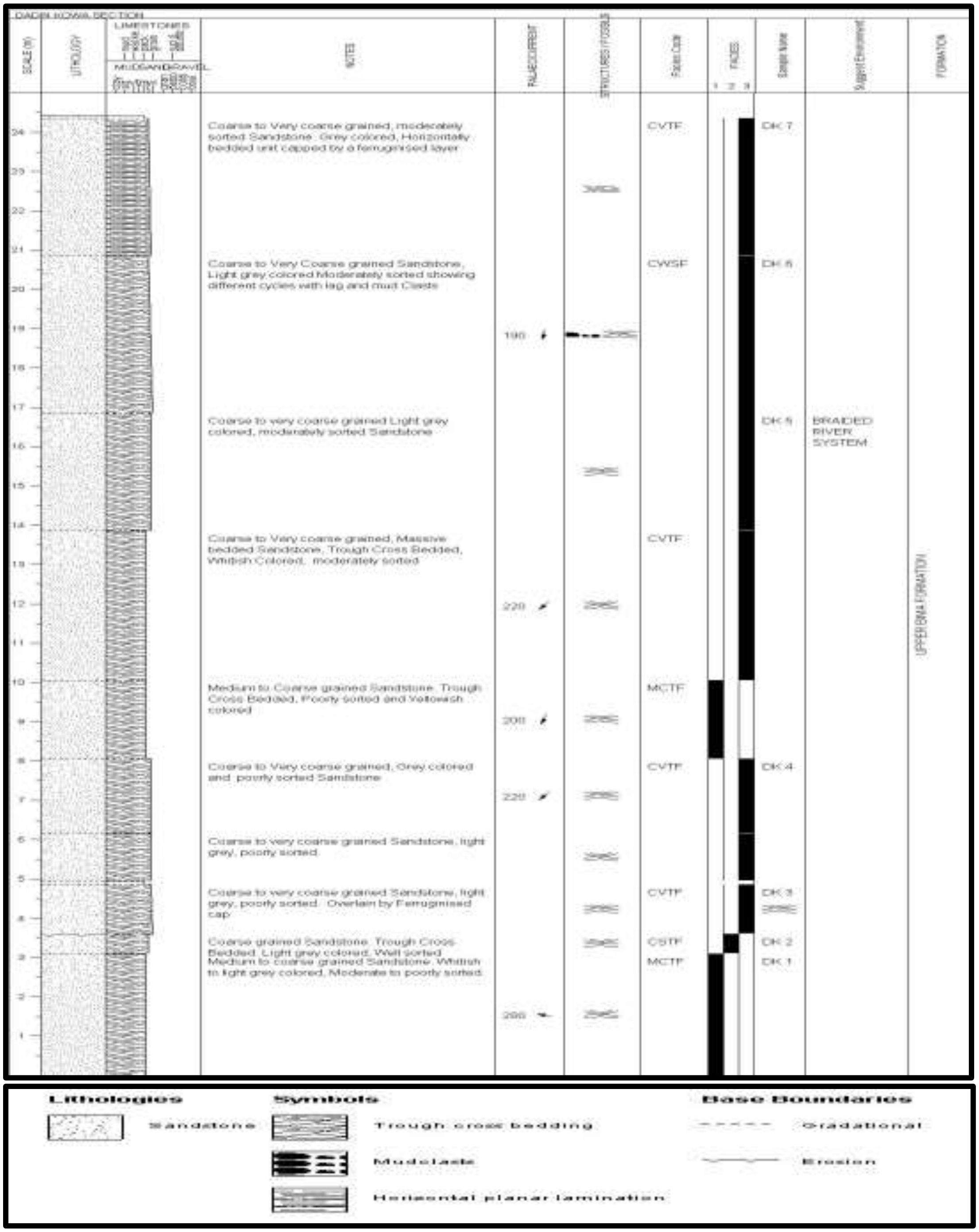

Fig. 8: Lithostratigraphic section of a Quarry around Yarandua with description of Lithologies, Sampling points, Facies, Facies association and Formation.

The MCTF facies (Fig. 9 b) is characterized by whitish to light grey, moderately to poorly sorted sandstone, exhibits trough crossbedding with a paleocurrent direction of 280°, with a total thickness of 5.1 m. The CSTF facies (Fig. 9c) is characterized by light grey, coarse-grained, well-sorted trough cross bedded sandstone with a thickness of 0.5 m. The CVTF facies (Fig. 9d) is described as consisting of coarse-grained sandstone, overlain by a thin layer (5–10 cm thick). The total thickness of the facies measures 5.25 m.

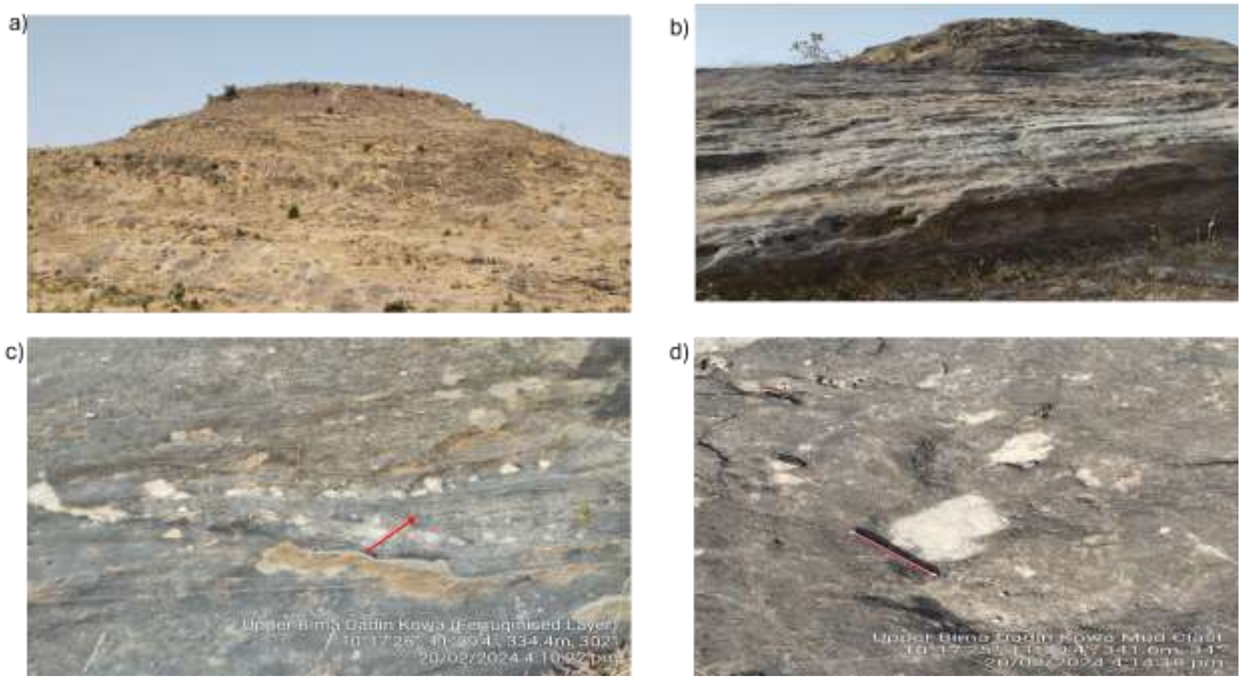

Fig. 9: The Dadinkowa section: a) Upper Bima hill, b) *Medium to coarse Trough Cross Bedded Sandstone, c): Coarse to very Coarse Trough cross-bedded Sandstone with mud clast (red arrow), d) Coarse to very Coarse Trough Cross-bedded sandstone*

Granulometric Analysis

Twenty-nine (29) sandstone samples were analyzed for granulometric analysis.

Univariate grain size parameters

Based on the data calculated in Table 1 using the Folk and Ward (1957) approach, the univariate parameters show the following results and their various interpretation:

Table 1: Granulometric Analysis Results of Sandstone Samples from Yarandua and Dadin Kowa

S/N)	SAMPLE	MEAN (Mz)	STANDARD VIATION (δi)	INCLUSIVE EWNESS (SKi)
1	DK 1	0.90 Coarse sand	1.86 Poorly sorted	-0.01 Near Symmetrical
2	DK 2	0.87 Coarse sand	1.24 Poorly sorted	0.26 Strongly fine- wed
3	DK 3	1.4 Medium ıined Sand	1.33 Poorly sorted	0.12 Fine skewed
4	DK 4	0.83 Coarse sand	1.44 Poorly sorted	0.08 Near Symmetrical
5	DK 5	0.73 Coarse sand	1.45 Poorly sorted	0.53 Strongly fine- wed
6	DK 6	0.93 Coarse sand	1.51 Poorly sorted	0.12 Fine skewed
7	YR 1	0.13 Coarse sand	1.53 Poorly sorted	0.04 Near symmetrical
8	YR 2	0.48 Coarse sand	1.64 Poorly sorted	0.08 Near symmetrical
9	YR 3	0.68 Coarse sand	1.56 Poorly sorted	0.1 Near symmetrical
10	YR 5	0.60 Coarse sand	1.70 Poorly sorted	-0.07 Near symmetrical

11	YR 6	0.73 Coarse sand	1.47 Poorly sorted	0.21 Fine skewed
12	YR 7	0.55 Coarse sand	1.33 Poorly sorted	-0.08 Near symmetrical
13	YR 9	-0.60 Very arse Sand	1.38 Poorly sorted	0.13 Fine skewed
14	YR 10	0.88 Coarse sand	1.83 Poorly sorted	0.12 Fine skewed
15	YR 11	0.53 Coarse sand	1.61 Poorly sorted	0.17 Fine skewed
16	YR 12	0.98 Coarse sand	1.46 Poorly sorted	0.04 Near symmetrical
17	YR 13	0.67 Coarse sand	1.87 Poorly sorted	-0.002 Near symmetrical
18	YR 14	0.53 Coarse sand	1.64 Poorly sorted	0 Near symmetrical
19	YR 15	-0.03 Very arse Sand	1.19 Poorly sorted	-0.02 Near symmetrical
20	YR 16	1.17 Medium ined Sand	1.84 Poorly sorted	0.07 Near symmetrical
21	YR 17	0.50 Coarse sand	1.83 Poorly sorted	0.11 Fine skewed
22	YR 19	-0.22 Very arse Sand	1.59 Poorly sorted	0.12 Fine skewed
23	YR 21	-0.10 Very arse Sand	1.66 Poorly sorted	0.22 Fine skewed
24	YD 1	-0.18 Very arse Sand	1.28 Poorly sorted	0.18 Fine skewed
25	YD 2	0.13 Coarse sand	1.45 Poorly sorted	0.16 Fine skewed
26	YD 3	0.35 Coarse sand	1.15 Poorly sorted	0.34 Strongly fine- wed
27	YD 4	0.53 Coarse sand	1.38 Poorly sorted	0.09 Near symmetrical
28	YD 5	0.70 Coarse sand	1.71 Poorly sorted	0.26 Fine skewed
29	YD 8	-0.27 Very arse Sand	1.46 Poorly sorted	0.11 Fine skewed

Bivariate Analysis

Folk and Ward's (1957) statistical grain-size parameters, mean, standard deviation (sorting), skewness, and kurtosis, have long been fundamental in sedimentological studies for interpreting depositional environments. These parameters help identify sedimentary processes by analyzing grain-size distributions. Bivariate plots, such as mean versus standard deviation and skewness versus standard deviation, are commonly utilized. These findings align with the original concepts proposed by Folk and Ward (1957), emphasizing the significance of grain-size statistical analysis in reconstructing past depositional environments.

Mean vs. Standard Deviation

The positioning in the river field (Fig. 10) suggests that the sediments exhibit a comparatively higher standard deviation (indicating poorer sorting) and diverse mean grain sizes. This demonstrates the dynamic characteristics of river currents, which carry various grain sizes due to changes in energy levels. This is typical of river systems with episodic high-energy events (e.g., floods) and reworked deposits (Folk & Ward, 1957).

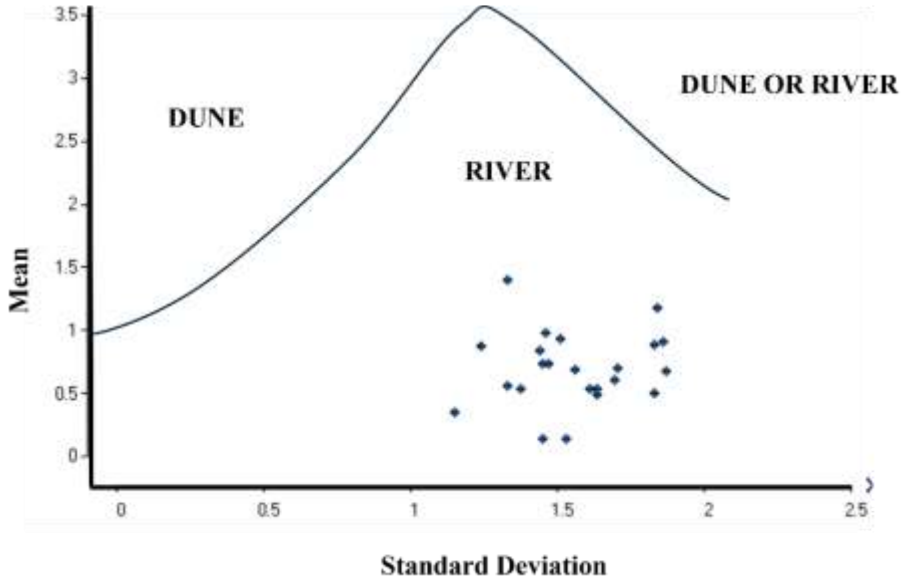

Fig. 10: Bivariate plot of Mean Vs Standard Deviation

Skewness vs. Standard Deviation

The skewness-sorting plot (Fig. 11) falls within the river field, it indicates that the grain-size distribution is asymmetric which the characteristic of river deposits is. Skewness values, either slightly positive or negative, signify a combination of finer and coarser materials, reflecting the sediment reworking processes found in a fluvial environment. The coarser bedload is indicative of alternating low- and high-energy flow regimes in rivers (Boggs, 2009)

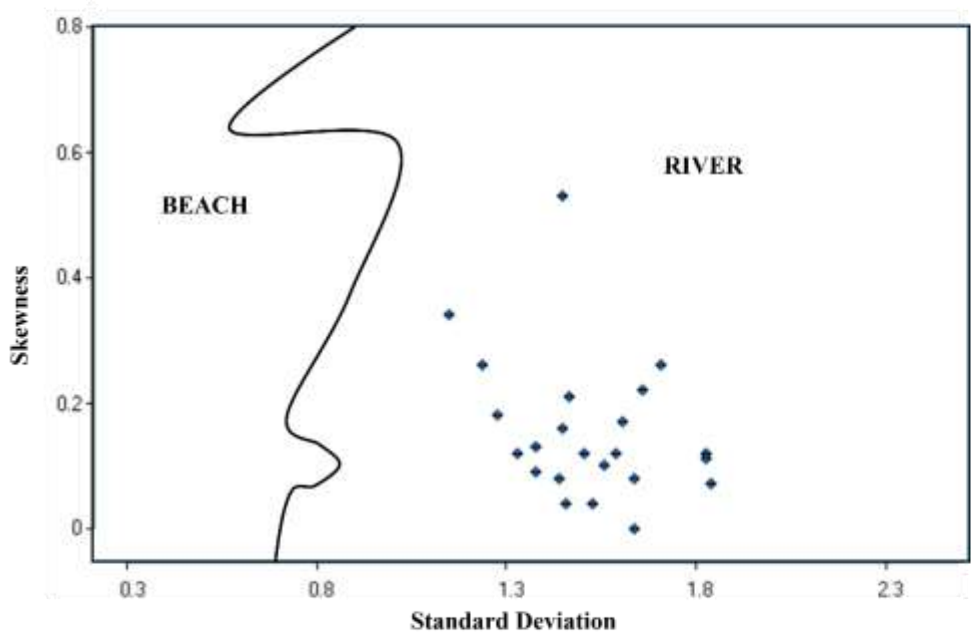

Fig. 11: Bivariate plot of Skewness Vs Standard Deviation

Skewness vs. Mean

This plot (Fig. 12) aligns with the river process and further confirms that the central tendency and asymmetry of the grain sizes are consistent with a depositional setting dominated by water flow. This indicates a balanced admixture of sediments brought in by river processes. These trends highlight the interplay between flow energy and sediment supply in rivers (Folk & Ward, 1957; Boggs, 2009).

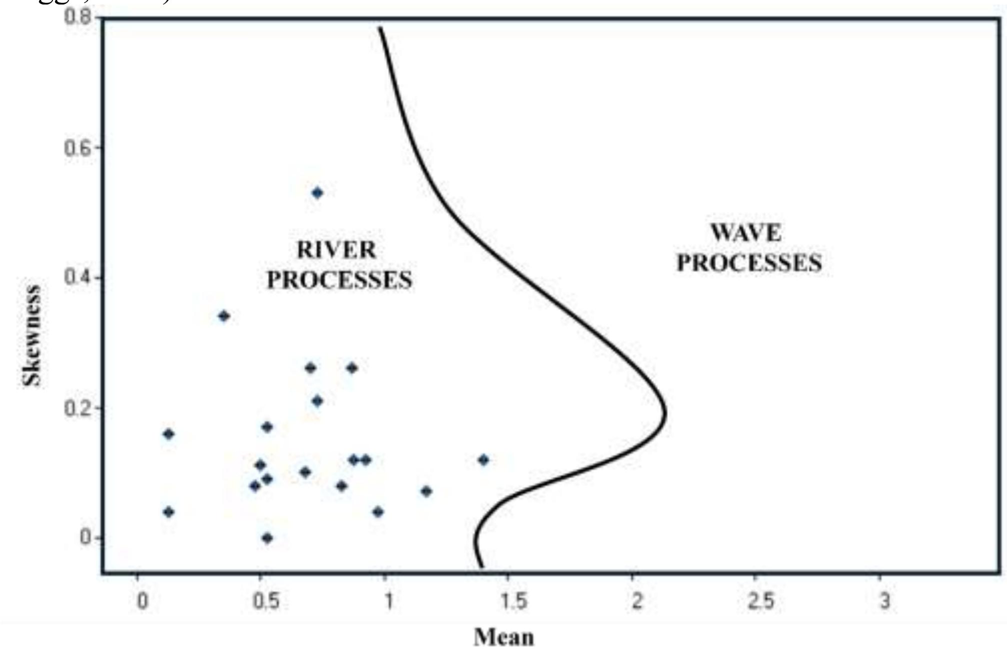

Fig. 12: Bivariate plot of Skewness Vs Mean

Conclusion

The integrated facies and granulometric analyses of the Bima Formation in Yarandua and Dadinkowa reveal a dynamic depositional system predominantly influenced by fluvial processes. The vertical arrangement of facies beginning with matrix-supported conglomerates (MSCPF) at the base, followed by trough cross-bedded coarse sandstones (CVTF, MCTF), and culminating in finer-grained floodplain deposits (PCMSF, PCMFF) illustrates a transition from a progradational alluvial fan to a braided river system.

Grain size parameters, including coarse mean sizes, poor sorting, and positive skewness, support the interpretation of bedload-dominated transport occurring under fluctuating high-energy conditions typical of braided stream environments. Furthermore, bivariate plots consistently position the samples within the river field.

The depositional environment of the Bima Formation in this region has evolved from proximal high-gradient debris flows to distal floodplain and bar deposits. This evolution reflects episodic sedimentation related to tectonic activity in the Upper Benue Trough.

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