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Fluvial sedimentology of the river Ethiope sediments, Niger Delta, Southern Nigeria

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Abstract

Despite modern advances in the study of rivers globally, there remains a plethora of work to be done especially in the area of fluvial sedimentology of some present-day river systems. Previous studies on fluvial sedimentology of the sediments of the river Ethiope (in southern Nigeria) are meagre. Grain size analytical methods are indispensable to infer siliciclastic sediments' hydrodynamic conditions, transportation mode(s), and sedimentary environments. Twenty-eight samples *(n=28)* of the river Ethiope sediments were selected and studied using granulometric analyses (mechanical sieving and pebble morphometric methods). The granulometric analyses results revealed that the obtained sediments were comprised of 82.75% sand, 9.33% gravel, and 7.92% mud. A ternary diagram of sand-gravel-mud shows the sediments are mainly gravelly sand, with few indicating slightly gravelly sand, gravelly muddy sand, muddy sand, and sandy gravel. The grain size statistical analysis shows that the river Ethiope sediments consist of medium to coarse, poorly-sorted to moderately well-sorted, strongly coarse skewed to strongly fine skewed, and very platykurtic to extremely leptokurtic sands. The pebble morphometric analysis revealed that the pebbles range in shape from bladed (B) 22%, compact-bladed (CB) 17%, compact (C) 16%, compact-platy (CP) 16%, compact-elongated (CE) 12%, platy (P) 5%, to elongated (E) 5%. The integration of bivariate plots, ternary diagrams, and C-M patterns plotted for the sediments of the river Ethiope indicated a fluvial environment with sediments characterised by low to moderately high energy that transport sediments of different sizes and grades through saltation, traction, and suspension modes. This study also confirms that sediment transport modes such as saltation, traction, and suspension typify river environments. In general, the existing sedimentologic models derived from grain size analysis of sediments and pebble morphometric methods obtained from modern-day rivers can be applied to better understand transport modes, sedimentary processes, and palaeoenvironments of their ancient counterparts.

Keywords:
River Ethiope Nigeria; fluvial sedimentology; sediments texture; sediment transport; hydrodynamic conditions

1. Introduction

The existence of river(s) has been known to immensely contribute to the development of early to present-day civilisation and the ecosystems regarding access to sustainable water resources, mineral resource exploration/exploitation, green energy supply, transportation, recreation, etc. The Ethiope River in the Niger Delta Basin is not an exception; a significant source of water, mineral resources (sands and pebbles) for construction purposes, transportation of timbers, and hospitality/recreational facilities (resorts located along the river banks) to the various communities whose founding is closely related to the existence of this river. Geologically, rivers represent a unique sedimentary environment (continental) marked by processes of erosion, transportation, and deposition of sediments (depending on the flow velocity and the nature of deposits) (**Dill et al., 2022**). The flow rate of rivers is often heterogeneous, and their bed load is varied, containing different grain sizes ranging from gravel, sand, and silt to clay (e.g. **Boggs, 2009; Sherman et al., 2013**). During its existence, a river system goes through the stages of young, mature, and old. Fluvial facies in the rock record are numerous and have played host to hydrocarbons and water as they have served as significant hydrocarbon reservoirs and aquifers, respectively. Significantly, modern river systems are well-studied to better our understanding of how ancient fluvial facies operated (**Sames, 1966; Friedman, 1961; 1967; Moiola and Weiser, 1968; Visher, 1969; Zhang et al., 2020; Adiotomre et al., 2021; Dill et al., 2022**).

Modern fluvial sedimentology has been a subject of interest for the past five decades (e.g. **Calgary, 1977; Miall, 1987; Adiotomre et al., 2021; Dill et al., 2022**). Its importance may span from an economic viewpoint

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because it can serve as a transport medium for mineral enrichment. Modern fluvial sedimentology has also been applied to making inferences on the sedimentary processes and depositional environment of their facies product (e.g. **Zhang et al., 2020; Adiotomre et al., 2021**). Textural characteristics of stream sediments can be applied to predict sedimentary processes involved in sediment transport (**Mycielska-Dowgiallo and Ludwikows-Kędzia, 2011; Saha et al., 2019**). Many authors, while attempting the reconstruction of a palaeoenvironment for ancient sediments, have often used modern sediments from both rivers and beaches (**Sames, 1966; Friedman, 1961; 1967; Moiola and Weiser, 1968; Visher, 1969; Mycielska-Dowgiallo and Ludwikows-Kędzia, 2011; Adiotomre et al., 2021**). They were able to establish a correlation between the products of both modern and ancient environments. Comparative studies involving palaeoenvironmental reconstructions for ancient sediments using insight from modern sediments also exist (e.g. **Sames, 1966; Visher, 1969; Friedman and Sander, 1978; Selley, 2000; Boggs, 2009**). Textural characteristics of clastic sediments or sedimentary rocks are important characteristics that reflect sedimentary processes and environments. Sedimentary processes are however similar in most sedimentary environments and consequently their sedimentary products often exhibit similar textural characteristics. Reconstruction of depositional environments from the analysis of grain size therefore requires integration of other data (such as sedimentary structures, composition, lithologic associations of sedimentary rocks, fossil contents) to textural characteristics of the ancient deposits. Such integration can thus serve as good tools for palaeoenvironmental reconstruction, provenance, prediction of geometry, and palaeogeographic studies (**Reading and Collinson, 1996; Adiotomre et al., 2021**).

Usually, a river system's mature and old stages are marked by the depositional sedimentary environment through the formation of flood plains and lateral accretion deposits, such as point bars (**Reineck and Singh, 1980**). Despite the invaluable role in fluvial sedimentation episodes, the mature and old stages in the river Ethiope have been taken over as it joins the Benin River, making the youthful stage dominant, as can be deduced from field studies. This study will thus highlight the fluvial sedimentology of the sediments entrained, their mode(s) of transportation and the sedimentary environment inherent in this youthful stage-dominated present-day river Ethiope.

The drainage area of the river Ethiope is delimited in the location map (see **Figure 1**). The geology of the study area is fully masked by a thick to thin veneer of Coastal Plain sands, alluvium, and Sombreiro-Warri Delta Plain sands. Previous studies aimed at the fluvial sedimentological characteristics of the Ethiope River sediments are meagre. This study aims to unravel the textural characteristics, sedimentary processes, and modes of transportation of fluvial sediments within the river Ethiope. It also included validating the application of modern fluvial sedimentology to solving problems related to how ancient fluvial sediments were transported and deposited. This study will be especially important in the areas of reservoir characterisation, environmental and community/urban development plans, and economic mineral resource exploitation. The porosity and permeability of hydrocarbon reservoirs and aquifers are fundamentally products of sediments defined by textural parameters (e.g. mean size, sorting, skewness, and kurtosis). The textural parameters are thus very crucial in the evaluation of hydrocarbon and groundwater resources. Studies of fluvial channel stability and flood control relied heavily on the characteristics/nature and rate of sediment supplied; as such, they are often needed in environmental and urban developmental plans. The sediments (mostly sands and gravel) of the river Ethiope are useful as construction material. However, effective and economic exploitation of this mineral resource requires an accurate definition of their textural characteristics (e.g. shape, size, sorting, etc.), distribution along the channel, etc.

2. Regional Geology of the Niger Delta Basin

The Niger Delta Basin, occurring in southern Nigeria, started development since Palaeocene as the rivers Niger, Benue, and Cross River transport and emptied their loads into the Southern Atlantic Ocean (**Doust, 1990; Reijer, 2011; Dim, 2017; Nwajide, 2022**). The delta is still actively prograding due to these rivers bringing sediments. The Cenozoic Niger Delta Basin comprises three regressive coarsening-upward stratigraphic units that occur mainly in the subsurface, namely from the oldest to the youngest: the Akata, the Agbada, and the Benin Formations (**Short and Stäuble, 1967; Doust, 1990; Reijers, 2011; Dim, 2017; Nwajide, 2022**). The Niger Delta Basin comprises about 12,000 m thick clastic wedge. The Akata Formation comprises about 90% of over-pressured and under-compacted shale and less than 10% sandstone. It was deposited in a marine environment, and its age varies from Eocene to Recent. Its thickness may be up to 6,400 m at the basin centre. The Agbada Formation consists of intercalations of shale and sandstone. Its environment of deposition is mixed marine and continental. Its thickness is about 4,000 m. Oligocene/Miocene to Recent age is assigned to the Agbada Formation. The youngest and topmost Benin Formation comprises over 90% sand/sandstone and less than 10% shale. It was laid down in a continental environment, with its age varying from Miocene to Recent. The Benin Formation may account for about 1,400 m of the Niger Delta Basin (**Short and Stäuble, 1967; Reijers, 2011; Dim, 2017; Nwajide, 2022**).

The Recent Niger Delta Basin is comprised of gravel, sand, mud, silt, and clay sediments. These Recent sedi-

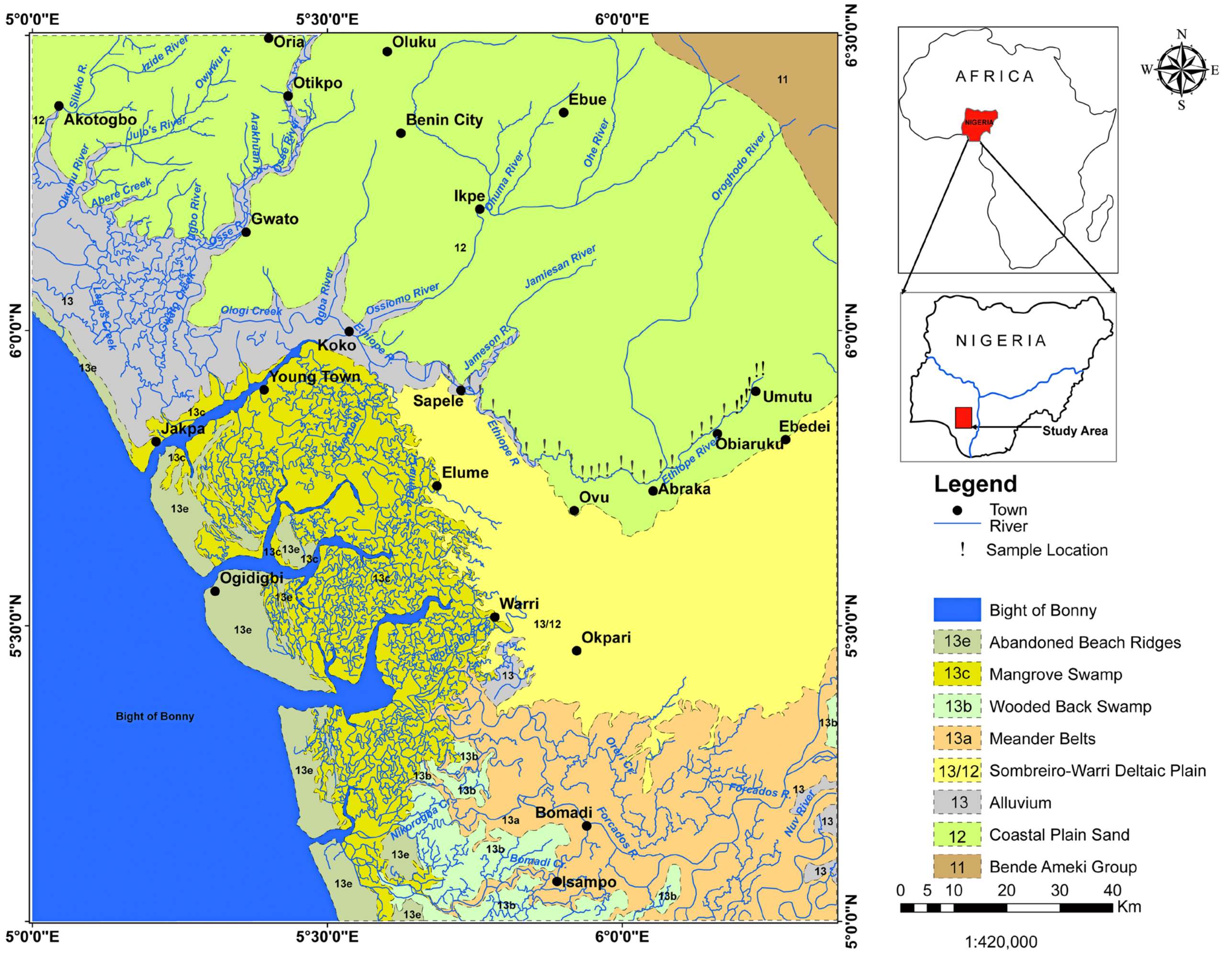

Figure 1: Location map of the study area

ments form thin layers that overlie the deposits of the Cenozoic Niger Delta Basin (**Short and Stäuble, 1967; Nwajide, 2022**). The river Ethiope cuts into parts of the Quaternary sediments of the Niger Delta Basin.

3. Materials and Methods

3.1. Location of the study area

The current study area lies between latitudes 5⁰ 39’ 00” and 6⁰ 09’ 00” N and within longitudes 5⁰ 01’ 00” and 6⁰ 18’00” E, covering the catchment areas of the river Ethiope (see **Figure 1**). The river Ethiope is a major river within the Niger Delta Basin, Southern Nigeria. The river took its source at *Umuaja* (less than 1 km away from *Umutu*), flows SW-NE, and turns to the NW-SE direction before joining the Benin River. It has a variable width ranging from about 4 to 55 m and a depth of 5 to 15 m; it, however, widens and deepens south-westwards. Its total length has been estimated at 50 km. The river empties its load into the Benin River for onward transportation into the Atlantic Ocean in *Sapele* area (see **Figure 1**). The river has a parallel drainage pattern that probably originated as a flow from a shallow, buried, unconfined aquifer highly supported by groundwater’s contribution. This is most likely why the river is perennial.

3.2. Sediments sampling and Flow Velocity measurements

The river sediments (*n=28*) were collected directly into the sample container by a diver using a scoop, sealed and labelled at the surface. The diver, usually stationed downstream of the sample site, exercises caution not to disturb the fine-grained sediment at the substrate surface. The river sediments were obtained at different locations (along the base of the river channel) from the river source (at *Umuaja*) to Sapele, where it joins the Benin River. The service of a professional certified diver was employed, who took 500 g of river sediments at each location (see **Figure 1**). The samples were kept in polythene bags to prevent them from being contaminated. A Global Positioning Satellite system (GPS) (*GARMIN GPSMAP® 76CS$_X$* with inbuilt sensors and maps) was used for accurate sample locations. The samples were air-dried and classified in the laboratory based on textural variations into pebble and sand/fine fractions (sizes).

Measurement of flow velocities of rivers cannot be overemphasised since it is important and necessary for monitoring climate change's impact on water resources (e.g. **Dobriyal et al., 2017**). The flow velocity of a river can also aid in the better understanding of the trends of natural risks such as land erosion, flash floods, rock slides and avalanches. To prevent any of these hazards, it is therefore significantly important to establish effective management practices that can help reinstate degraded ecosystems. Flow velocity measurement of a river can serve as a means of knowing how water contributes to economic development and human well-being (**Acreman, 2001; Dobriyal et al., 2017**). Most important and related to this study is the fact that flow velocity determines the ability of the river to erode, transport/entrain, sort, and deposit sediments.

The flow velocity of the river Ethiope was measured using the float method. The time (t) to traverse a known distance (s) along the river channel by a float was recorded, and the velocity (s/t) was calculated. At least three velocity measurements were taken in each location and the average reading was calculated (e.g. **Hauet et al., 2008; Gordon et al., 2013**; **Dobriyal et al., 2017**). The choice of the locations for velocity measurements depends largely on accessibility, safety considerations (especially where field crew and measurement facilities can be safely deployed) and the local authority permit bureaucracy. However, access permits were granted for localities such as *Umutu*, *Obinomba*, *Obiaruku*, and *Abraka* and velocity measurements were obtained. The application of this method in this study is expedient because it is fast, cost effective, non-polluting, and ease of the measurement procedure. Moreso, it has been reported that this method is appropriate for narrow and relatively straight rivers (e.g. **Hudson, 2004; Dobriyal et al., 2017**) like the river Ethiope. The float method is however an inaccurate method because the readings may be affected by vertical turbulent motion (e.g. **Dobriyal et al., 2017**).

3.3. Sediment grain size analysis

Both mechanical sieving and pebble morphometric techniques were applied to decipher the particle sizes of the river sediments. The mechanical sieving method described the sand fractions (**Friedman and Sanders, 1978; Boggs, 2009**). All samples were selected for the grain size analysis by mechanical sieving method following procedures in **Friedman and Sanders (1978)**. One hundred grams of each sample were weighed in a digital balance and sieved in a set of sieves stacked together in decreasing order of their sieve sizes from top to bottom. The per cent weight retained and the cumulative weight per cent (cumulative frequency) were calculated. Both frequency and cumulative frequency curves were plotted. The cumulative frequency curves were plotted on both arithmetic and semi-log papers. The cumulative curves on arithmetic paper were used to compute textural statistical parameters (graphic mean, standard deviation, graphic skewness, and graphic kurtosis) (**Folk and Ward, 1957; Selley, 2000; Szczesniak et al., 2023**). Graphic mean size is considered a statistical parameter that specifies the overall particle distribution of sediment/sedimentary rock (e.g. **Friedman and Sanders, 1978; Boggs, 2009; Sherman et al., 2013; Ghaznavi et al., 2019**).The cumulative frequency curves on semi-log paper were applied to validate the importance of grain size as an environmental indicator (e.g. **Visher, 1969; Friedman and Sanders, 1978; Boggs, 2009; Mycielska-Dowgiallo and Ludwikows-Kędzia, 2011; Sherman et al., 2013; Ejeh et al., 2015; Ghaznavi et al., 2019; Etobro et al., 2020; Adiotomre et al., 2021; Kasim et al., 2023**).

Sahu (1983) introduced the multigroup multivariate discrimination functions for reconstructing environments of deposition using statistical parameters. **Sahu (1983)** proposed Eigenvector (V) equations (1) and (2):

$$V_1 = 0.48048M_Z + 0.62301\sigma_1^2 + 0.40602Sk_i + 0.44413K_G \quad (1)$$

$$V_2 = 0.24523M_z - 0.45905\sigma_1^2 + 0.15715Sk_i + 0.8393K_G \quad (2)$$

Where:

V_1 and V_2 - Eigenvectors,
M_z - Mean size,
σ_i - Standard deviation,
Sk_i - Skewness,
K_G - Kurtosis.

3.4. Pebble morphometric analysis

The pebble morphometric technique was adapted to establish the grain size distribution of the gravel load. One hundred pebbles ($n=100$) were collected for the pebble morphometric technique to determine the average size and to infer the processes involved in their transport. Three or four particles within the size range of 4-64 mm (i.e. the grain size of pebbles) were selected from the samples collected from each location to make up the 100 samples for the pebble morphometric analysis. Preference was however given to larger pebbles for easy measurements of the three axes. The long (L), intermediate (I), and short (S) axes of the pebbles were measured using a vernier calliper (e.g. **Dill et al., 2022**). The pebbles' roundness was virtually estimated using **Sames**' method **(1966)**. Grain roundness is a measure of the degree to which sharp edges of grains are smoothing and the degree of abrasion that a grain is subjected to during transport and deposition. The grain shape of sediment is a pointer to the distance of sediment transport. Calculations including flatness ratio (FR) (e.g. **Lutig, 1962; Madi and Ndlazi, 2020;** Equation 3), elongation ratio (ER) (**Lutig, 1962; Madi and Ndlazi, 2020;** Equation 4), flatness index (FI) (e.g. **Illenberger, 1991; Madi and**

Ndlazi, 2020; Equation 5), oblate-prolate index (OPI) (**Dobkins and Folk, 1970; Madi and Ndlazi, 2020;** Equation 6) and maximum projection sphericity index (MPSI) (e.g. **Sneed and Folk,1958; Madi and Ndlazi, 2020;** Equation 7), were computed. These equations have been applied by different authors, including **Sherman et al. (2013), Okon et al. (2018), Madi and Ndlazi (2020), and Kasim et al. (2023)** to discriminate the environments of deposition of sedimentary rocks.

$$Flatness\ Ratio(FR) = S / L \quad (3)$$

$$Elongation\ Ratio(ER) = S / I \quad (4)$$

$$Flatness\ Index\left(FI\right) = \frac{\left[L - I + S\right]}{L} \quad (5)$$

$$Oblate - Prolate\ Index\left(OPI\right) = 10\left\{\frac{L - I}{L - S} - 0.5\right\} {}^{S}\!\!/_{L} \quad (6)$$

$$Maximum\ Projection\ Sphericity\ Index(MPSI) = \left({}^{S^2}\!\!/_{LI}\right)^{1/3} \quad (7)$$

Where:

L - Long axis,
I - Intermediate axis,
S - Short axis.

4. Results and Discussion

4.1. Textural characteristics and distribution

The river sediments were analysed for their textural characteristics (grain size and shape). Hand specimen analysis of the river sediments showed that they comprise different sizes of sediments ranging from a few gravels (> 2,000 μm), sands (62.5-2,000 μm), to silt-clays (< 62.5 μm). The gravels are mainly quartz-rich pebbles with angular to rounded grains. Some pebbles occur on the river floor, with their long axes occasionally trending in the flow direction. The dominant sediment load of the river Ethiope consists of different sand varieties. The grain size analysis by sieving showed that the river sediment comprises gravels ranging from 0.20 to 49.80% (average 9.33%), and the sands vary from 46.20 to 98.40% (average 82.75%). In comparison, the mud fraction consists of 0.60 to 23.60% (average 7.92%) (see **Table 1**). A ternary diagram of gravel-sand-mud peaks plotted for the river Ethiope (see **Figure 2**) revealed that the river sediments are composed of six textural groups, namely: sand, gravelly sand, slightly gravelly sand, muddy sand, gravelly muddy sand, and sandy gravel. The river sediments are, however, dominantly gravelly sand, sand, and muddy sand (see **Figure 2**). Histograms drawn based on the per cent weight retained (see **Figures 3a-c**) showed that the river sediments exhibit mainly unimodal distribution of sandy grains with their grain size varying between zero (0) and two φ (i.e. between 1 and 0.24 mm). These suggest that the river sediment load is mainly sandy-sized fraction followed by gravel and mud fraction. These depicted that the river Ethiope sediments are moderate- to poorly-sorted. The mud, comprising both silt and clay fractions with grain size less than four φ, is generally rare (see **Figures 3a-c**).

According to **World Rivers** (**2020**) (https://worldrivers.net/2020/03/28/how-fast-are-rivers/), "a moderately fast river flows at ≈ 1.39 m/s (5 km/hr); while a fast-flowing river exceeds 6.94 m/s (25 km/hr), especially during floods or wet season". The river Ethiope showed a range of flow velocity values, from moderately fast flowing (0.81 m/s in the *Umutu* area near the source; 0.87 m/s in *Abraka*) to moderately flowing (0.29 m/s in *Obinomba*; 0.56 m/s in *Obiaruku* and other areas further away from the source (see **Supplementary Materials A**). The high percentage of both sandy and gravel fractions implies that river Ethiope is flowing with a moderately high velocity. The river sediment load along the course of the river Ethiope did not show any remarkable trend in the downstream sediment deposition; however, the gravel fraction is relatively high at its source area (i.e. *Umuaja*), where its gravel fraction may account for over 31.5% (i.e. UMJ-1 in **Table 1**). Its probable high flow velocity can also explain its relatively low mud fraction (average 7.23%). Such high-velocity flow may not permit the deposition of the fine fraction but might have been transported further downstream through the Benin River to the Atlantic Ocean.

4.2. Grain size statistical parameters

Grain size is one of the essential descriptive characteristics of siliciclastic sediments because it not only gives information about the sediment load of the transporting medium and environment, but also implies sediment availability at the source area. The grain size analysis revealed that the river sediments have a mean size ranging from 0.25 to 1.85 φ (average 0.86 φ); these were interpreted as comprising coarse to medium (averagely coarse) sand (**Table 2; Parthasarathy et al., 2016; Szczesniak et al., 2023**). These mean size ranges corroborate with sediments transported under relatively moderately high flow velocity. The absence or low fine grains attested to the medium to moderately high speed of the river Ethiope, allowing the winnowing of the fines through hydrodynamic processes.

The calculated standard deviation for the river Ethiope sediment varies from 0.54 to 1.20 φ (average 0.83 φ); these, according to **Folk (1974), Parthasarathy et al. (2016), Ghaznavi et al. (2019)**, implied moderately well-sorted to poorly-sorted (moderately-sorted) (see **Table 2**). The moderately well-sorted suggested that the winnowing of the sediments was active, while the poorly-sorted sediments indicated the absence of winnowing. The winnowing activities may be due to the moderately high energy flow of the river Ethiope. The presence and absence of winnowing activities imply that the river Ethiope's energy level fluctuates occasionally.

Table 1: Grain size composition (gravel, sand, and mud in %) of the river Ethiope sediments

Sample #	Coordinates	Gravel (%)	Sand (%)	Mud (%)	Total (%)
SAP-1	05º52’22” N/06º43’12”E	00.40	87.60	12.00	100
SAP-2	05º51’12”N/05º43’25”E	12.80	83.80	03.40	100
SAP-3	05º51’16”N/05º43’20”E	02.50	94.50	03.00	100
AMK-1	05º23’18”N/05º44’48”E	21.00	75.50	03.50	100
AMK-2	05º23’15”N/05º42’47”E	01.60	92.00	06.40	100
OKP-1	05º44’34”N/06º55’33”E	00.80	96.20	03.00	100
AGH-1	05º46’57”N/06º51’50”E	00.40	90.40	09.20	100
IGN-1	05º44’44”N/05º58’21”E	15.50	81.50	03.00	100
EKU-1	05º58’58”N/06º45’19”E	25.00	73.00	02.00	100
EKU-2	05º45’19”N/05º58’58”E	12.00	81.00	07.00	100
ORA-1	05º46’03”N/06º03’17”E	01.00	91.00	8.00	100
ORA-2	05º45’56”N/06º03’18”E	04.40	84.80	10.80	100
ORA-3	05º44’55”N/06º03’16”E	00.20	85.80	14.00	100
ERH-1	05º16’32”N/06º04’13”E	49.80	46.20	04.00	100
ABK-1	05º47’58”N/06º06’33”E	12.50	84.00	03.50	100
ABK-2	05º48’10”N/06º06’08”E	05.20	91.40	03.40	100
UMG-2	05º49’27”N/06º06’12”E	05.50	90.50	04.00	100
OBK-1	05º51’22”N/06º09’20”E	06.10	88.20	05.70	100
OBK-2	05º51’23”N/06º09’21”E	04.40	89.20	06.40	100
OBN-1	05º52’03”N/06º10’37”E	14.00	76.00	10.00	100
OBN-2	05º52’03”N/06º10’35”E	05.00	83.00	12.00	100
OWH-1	05º52’04”N/06º10’49”E	01.00	86.40	12.60	100
EBD-1	05º53’53”N/06º12’44”E	01.40	75.00	23.60	100
UMT-1	05º55’25”N/06º18’16”E	02.00	91.00	07.00	100
UMT-2	05º53’20”N/06º12’30”E	00.30	76.70	23.00	100
UMT-3	05º55’25”N/06º13’17”E	01.00	98.40	00.60	100
UMJ-1	05º56’03”N/06º13’58”E	31.50	64.50	04.00	100
UMJ-2	05º56’30”N/06º13’59”E	24.00	59.50	16.50	100
Min.		00.20	46.20	00.60	
Max.		49.80	98.40	23.60	
Mean		9.33	82.75	07.92	100

S # = Sample number; Min. = minimum; Max. = maximum

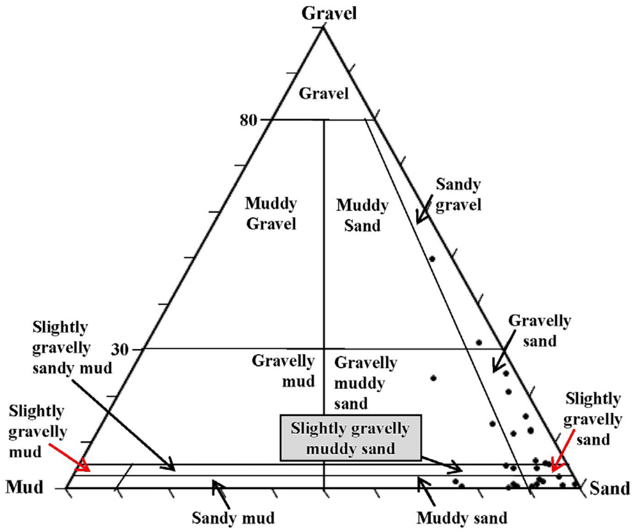

Figure 2: Gravel-Mud-Sand ternary diagram for the river Ethiope sediments. The black dots show the fields where the river Ethiope sediments fall (modified after **Folk, 1980**)

4.3. Pebble morphometric parameters

The results of pebble morphometric studies show that the long axes (L) of the analysed pebbles vary from 10.4 to 72.3 mm, with an average value of 33.3 mm; the intermediate axes (I) range from 6.14 to 53.2 mm, with an average value of 25.6 mm; and the short axes (S) range from 1.68 to 41 mm, with an average value of 17.1 mm. The estimated roundness of the pebbles varies from 15 to 60% (average of 42.2%) (see **Supplementary materials B**). The flatness ratio (S/L) ranges from 0.32 to 0.54, with an average of 0.50. Over 90% of the flatness ratio is more significant than 0.45 (see **Supplementary Materials B**), suggesting a fluvial environment (**Madi and Ndlazi, 2020**). The elongation ratio (I/L) varies from 0.47 to 0.77 (average of 0.7). Over 90% of the studied pebbles have elongation ratios within 0.6 and 0.90, the threshold for fluvial setting. The analysed pebbles’ calculated oblate-prolate indices (OPI) range from -0.09 to 0.07 (average of 0.00). All the analysed pebbles

Table 2: Computed textural parameters (M_z, σi, Ski, and K_G) and characteristics of the river Ethiope sediments

S. #	**M_z(Φ)**	**σ_i(Φ)**	**Sk_i**	**K_G**	**Sediments' characteristics**
SAP-1	1.25	0.79	0.10	2.82	Medium sand, moderately-sorted, nearly symmetrical, very leptokurtic
SAP-2	0.45	1.09	-0.24	2.46	Coarse sand, poorly-sorted, coarse skewed, very leptokurtic
SAP-3	0.73	0.54	-0.37	3.38	Coarse sand, moderately well-sorted, strongly coarse skewed, extremely leptokurtic
AMK-1	0.25	1.2	0.09	0.92	Coarse sand, poorly-sorted, nearly symmetrical, mesokurtic
AMK-2	0.90	0.64	-0.03	5.12	Coarse sand, moderately well-sorted, nearly symmetrical, extremely leptokurtic
OKP-1	1.13	0.82	0.37	6.19	Medium sand, moderately-sorted, strongly fine skewed, extremely leptokurtic
AGH-1	1.17	0.59	0.32	8.52	Medium sand, moderately well-sorted, strongly fine skewed, extremely leptokurtic
IGN-1	0.25	1.20	-0.25	2.44	Coarse sand, poorly-sorted, coarse skewed, very leptokurtic
EKU-1	0.64	0.58	0.16	0.66	Coarse sand, moderately well-sorted, fine skewed, very platykurtic
EKU-2	0.87	0.86	-0.09	2.16	Coarse sand, moderately-sorted, nearly symmetrical, very leptokurtic
ORA-1	1.13	0.76	-0.21	2.59	Medium sand, moderately-sorted, coarse skewed, very leptokurtic
ORA-2	0.88	0.70	-0.32	3.40	Coarse sand, moderately well-sorted, strongly coarse skewed, extremely leptokurtic
ORA-3	1.12	0.86	-0.04	6.38	Medium sand, moderately-sorted, nearly symmetrical, extremely leptokurtic
ERH-1	0.42	0.71	1.34	1.28	Coarse sand, moderately well-sorted, strongly fine skewed, leptokurtic
ABK-1	0.40	0.98	-0.38	2.28	Coarse sand, moderately sorted, strongly coarse skewed, very leptokurtic
ABK-2	0.63	0.65	-0.10	2.65	Coarse sand, moderately well-sorted, coarse skewed, very leptokurtic
UMG-2	0.87	0.76	-0.49	3.30	Coarse sand, moderately sorted, strongly coarse skewed, extremely leptokurtic
OBK-1	0.84	0.86	-0.06	2.38	Coarse sand, moderately-sorted, nearly symmetrical, very leptokurtic
OBK-2	0.98	0.90	-0.22	3.01	Coarse sand, moderately-sorted, coarse skewed, extremely leptokurtic
OBN-1	0.61	1.15	0.073	2.53	Coarse sand, poorly-sorted, nearly symmetrical, very leptokurtic
OBN-2	1.03	1.12	-0.06	3.34	Medium sand, poorly-sorted, nearly symmetrical, extremely leptokurtic
OWH-1	1.17	0.88	0.01	3.48	Medium sand, moderately-sorted, nearly symmetrical, extremely leptokurtic
EBD-1	1.27	0.63	-0.30	2.31	Medium sand, moderately well-sorted, strongly coarse skewed, very leptokurtic
UMT-1	0.93	0.85	-0.05	3.01	Coarse sand, moderately-sorted, nearly symmetrical, leptokurtic
UMJ-1	0.53	0.63	0.62	0.52	Coarse sand, moderately well-sorted, strongly fine skewed, very platykurtic
UMJ-2	0.93	1.04	0.62	0.94	Coarse sand, poorly sorted, strongly fine skewed, mesokurtic
UMT-2	1.85	1.04	0.06	3.53	Medium sand, poorly-sorted, nearly symmetrical, extremely leptokurtic
UMT-3	0.73	0.55	0.05	2.46	Coarse sand, moderately well-sorted, nearly symmetrical, very leptokurtic
Minimum	0.25	0.54	-0.49	0.52	
Maximum	1.35	1.20	1.34	8.52	
Average	0.86	0.84	0.02	3.00	Coarse sand, moderately-sorted, nearly symmetrical, very leptokurtic

S# = Sample number; *Mz = mean size (values in Φ); σi = sorting or standard deviation (in Φ); Ski = skewness; KG =* kurtosis.

have OPI greater than -1.50 (see **Supplementary Materials B**), signifying deposition under fluvial processes (**Dobkins and Folk, 1970; Okon et al., 2018; Madi and Ndlazi, 2020**).

The maximum projection sphericity index (Ψp) varies from 0.15 to 0.94 (average of 0.71). 75% of the analysed pebbles have a maximum projection sphericity index greater than 0.65 (see **Supplementary Materials B**), depicting that they are fluvial deposits (e.g. **Hubert, 1968; Dobkins and Folk, 1970; Okoro et al., 2012; Okon et al., 2018**). From the calculated values of the flatness ratio, the elongation ratios, the oblate-prolate index, and the maximum projection sphericity index, it can be inferred that fluvial processes transported the studied pebbles.

Sphericity is a measure at which the shape of a pebble approaches that of a sphere. **Sneed and Folk's (1958)** pebble shape classification was also adapted in this study. A ternary diagram of the ratio of the short (S) to long (L) axes peak, intermediate (I) to long (L) axes peak, and (L-I)/L-S) the peak was also plotted for the pebbles of river Ethiope to ascertain their forms (see **Figure 4a**).

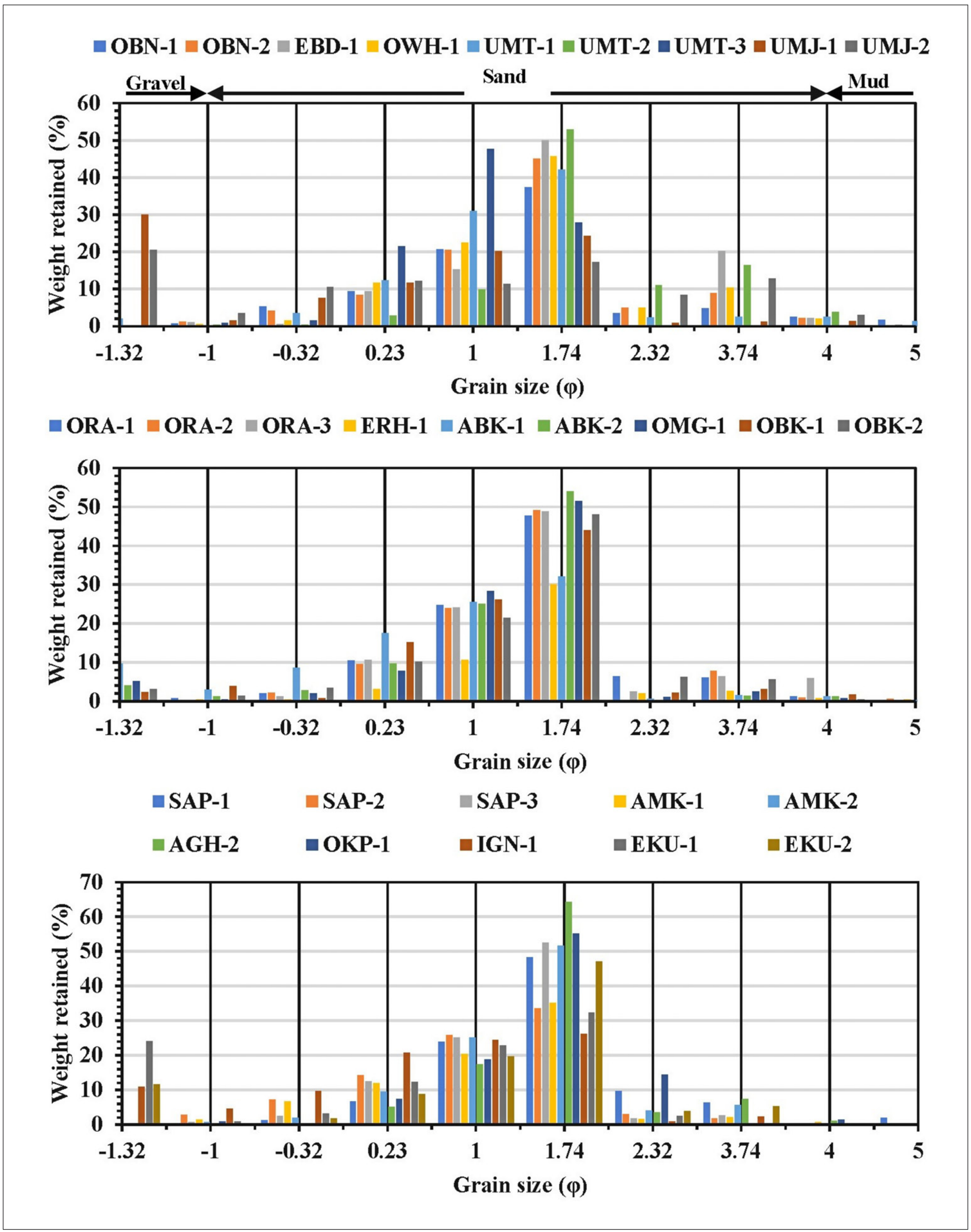

Figure 3: Histograms of the analysed samples of the river Ethiope showing a mainly unimodal distribution of the sandy fractions. (a): Histograms of the river Ethiope load between UMJ-1 (source area) and OBN-1. (b): Sediment distribution between OBK-2 and ORA-2. (c): River load from EKU-2 to SAP-3.

The sphericity-form ternary diagram revealed that the pebbles were of different forms ranging from bladed (B) 22%, compact-bladed (CB) 17%, compact (C) 16%, compact-platy (CP) 16%, compact-elongated (CE) 12%, platy (P) 5%, elongated (E) 5%, very-bladed (VB) 3%, very platy (VP) 2%, and 2% very elongated (VE) (see **Figure 4a; Sherman et al., 2013**). **Zinng (1935)** attempted the classification of pebble shape using a bivariate diagram of the ratio of intermediate to long axes (i.e. I/L) versus the ratio of short to intermediate axes (i.e. S/I). He classified the pebble shape into prolate, oblate, equant and bladed. Following Zinng's classification, a bivariate diagram was plotted for the pebbles recovered from the river Ethiope (see **Figure 4b**). The bivariate chart showed that the shapes of the pebbles are largely equant, oblate (disk-shaped), while few are prolate (roller) (**Selley, 2000; Sherman et al., 2013**). Bladed pebbles are generally rare in the river Ethiope.

4.4. Bivariate plots in relation to transport modes and sedimentary environment

The shape of grains of siliciclastic sediments is an important characteristic that may be used to predict the degree of abrasion, provenance, the distance of transport, the behaviour of rivers, modes of sediments transport,

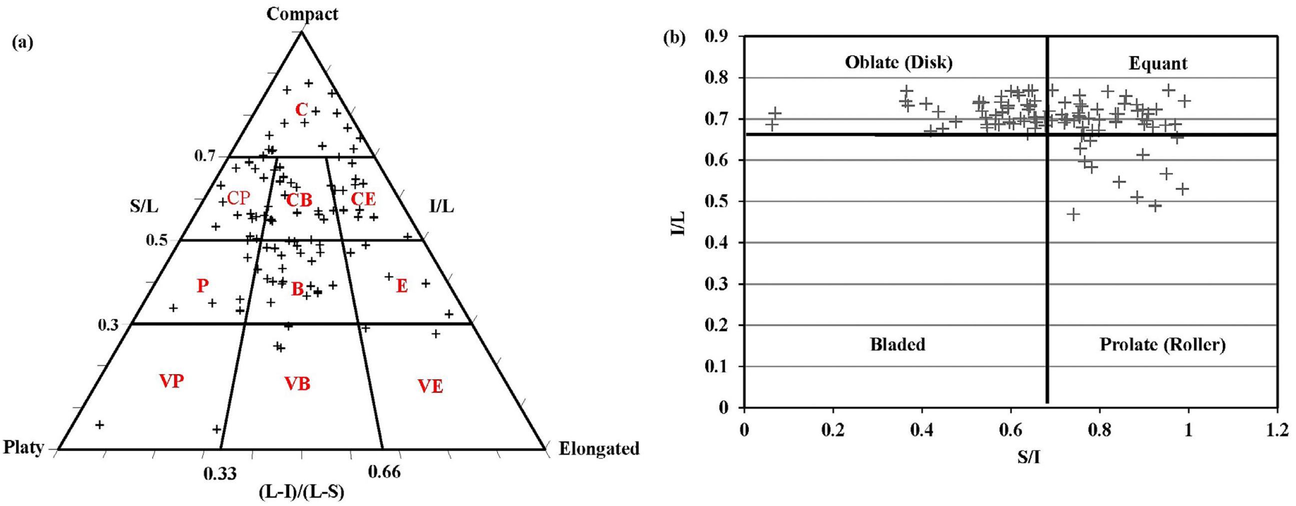

Figure 4: Shape of the pebbles of the river Ethiope. (a) A ternary diagram of the ratio of the short axis to the long axis (S/L), intermediate to the long axis (I/L), and (L-I)/L-S) peaks classification of pebble shapes on the river Ethiope. Where: V = very, B = bladed, C = compact, E = elongated, and P = platy (modified after **Sneed and Folk, 1958; Sherman et al., 2013**); (b) Bivariate plot of I/L against S/I (modified after **Zinng, 1935; Selley, 2000; Sherman et al., 2013**).

and sedimentary processes (e.g. **Krumbein, 1941; Friedman and Sander, 1978; Mycielska-Dowgiallo and Ludwikows-Kędzia, 2011; Sherman et al., 2013; Ghaznavi et al., 2019; Adiotomre et al., 2021; Kasim et al., 2023**). Transport mode may control transporting media's sorting, sediment transport, and morpho-dynamic feedback. The angular to the rounded shape of the sand grains of the river Ethiope depicts short to long distances of transport. The short to long-distance transport further implies multiple source areas for the sandy sediments. The angular to rounded quartz pebbles that dominate the gravels of the Ethiope also suggest short to long transport distances, respectively. **Visher (1969)** established different transporting modes when plotting cumulative frequency curves on semi-log papers for modern rivers and beach sediments. **Visher (1969)** also demonstrated that river sediments are typified by a two-pattern while beach sediments are typified by a 3-pattern sediment distribution. Cumulative frequency curves were plotted on the semi-log scale for the river Ethiope sediments (**Figures 5a** and **b**). The curves showed that river Ethiope sediments were transported by saltation and suspension processes; however, some of the analysed samples indicated a 3-pattern distribution comprising traction, saltation, and suspension populations. The 2-pattern distribution showed that most of the sediments of the river Ethiope were transported by saltation process while few types of sediment as suspension process. The 3-pattern distribution revealed that most of the size distributions of the sediments of the river Ethiope were transported as saltation, a few sediment types as suspension, and very few sediment types were transported as traction loads (see **Figures 5a-b**). The 2-pattern population further revealed that the coarse, the medium, and the fine sands were transported by the saltation process while the very fine sediments were entrained as suspension loads. The 3-pattern population (comprising saltation, suspension, and traction) suggested that the traction process occasionally operate and led to the entrainment of the few very coarse sands of the river Ethiope (see **Figures 5a** and **b**). The cumulative frequency curves of the river Ethiope sediments agree with the models that generally typify those of Visher's river systems (**1969**).

4.4.1 The C-M pattern and transportation mechanisms/environment

A bivariate plot of C (one percentile distribution) versus M (median percentile distribution), known as the Passega C-M pattern (on log probability scales), has been applied to decipher the transport mode(s) and depositional environment(s) of siliciclastic of varied sources by **Passega** (**1957; 1964**). Following the research works by **Passega (1957, 1964),** C-M patterns have been widely applied in sediments' transportation mechanisms/hydrodynamics and depositional environment(s) diagnosis (e.g. **Passega and Byramjee, 1969; Mycielska-Dowgiallo and Ludwikows-Kędzia, 2011; Parthasarathy et al., 2016; Baiyegunhi et al., 2017; Ghaznavi et al., 2019; Ahmad et al., 2020; Adiotomre et al., 2021; Kasim et al., 2023**). The C-M values for the river Ethiope sediments are plotted in the O-P region (corresponding to rolling and suspension) of the original Passega's plot and within the P-Q (corresponding to saltation and rolling) region of the **Ludwikows-Kędzia (2000)** C-M diagram (a modification of the original Passega's C-M pattern) (see **Figure 6**). **Passega (1964)** reported that a lower Cs limit is inversely proportional to increasing depth in a marine depositional basin, associated with turbulence and wave activity, which decreases towards the deeper basin part. Conversely, in a fluvial environment

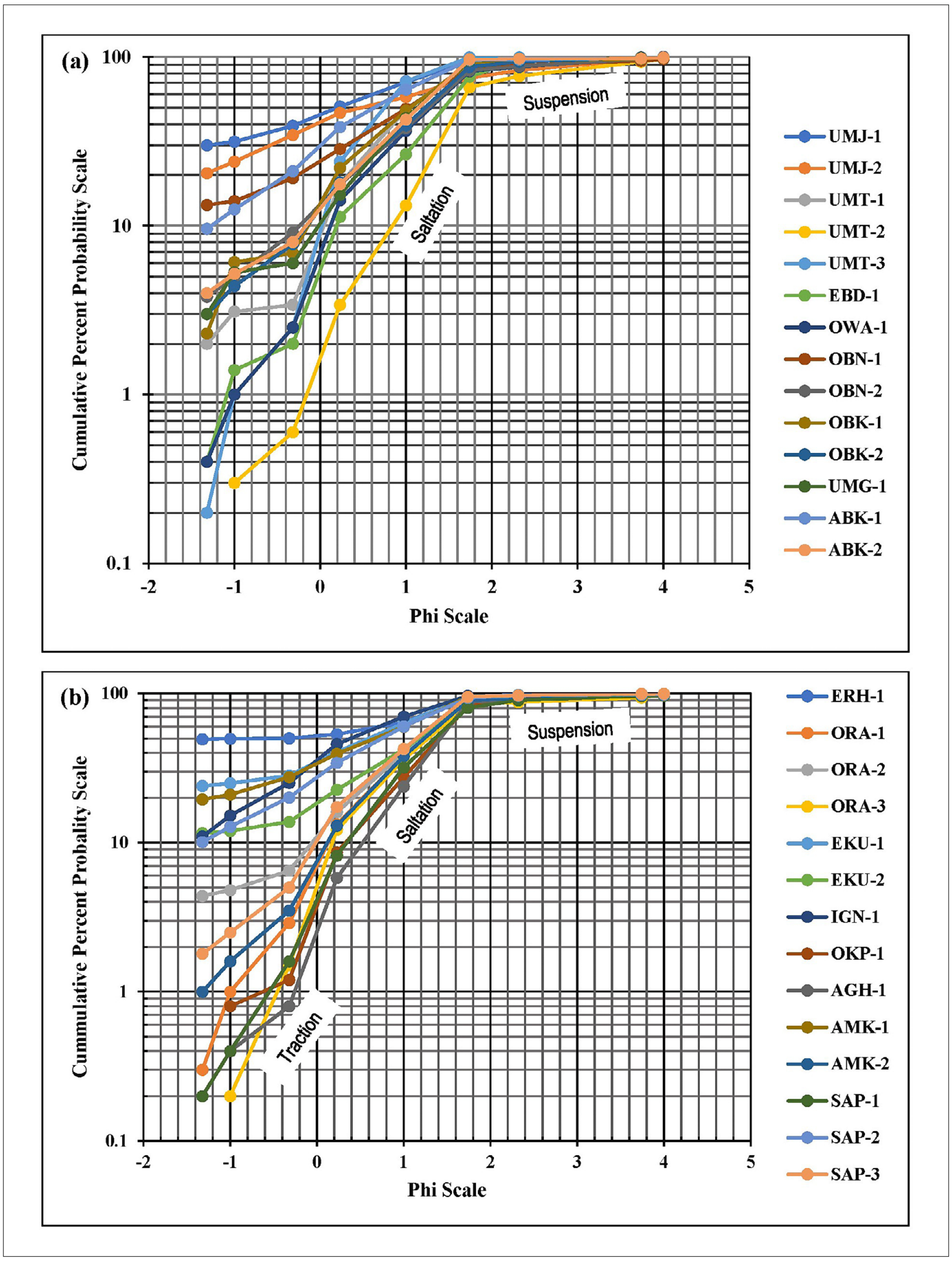

Figure 5: Log-probability curves (after **Visher, 1969**) of sediment samples from the river Ethiope showing the different transport modes: suspension, saltation, and traction; (a) Samples UMJ-1 to ABK-2; (b) Samples ERH-1 to SAP-3.

with varying gradients and current dynamics, it gives rise to higher C-values (higher values of C_u and C_s (**Mycielska-Dowgiallo and Ludwikows-Kędzia, 2011**). An upward shift in the C-values above the C-M pattern of Passega was also observed in this study. However, most affected values fell within the **Ludwikows-Kędzia (2000)** C-M diagram (see **Figure 6**). Such an upward shift in C-values has been frequently reported as closely related to the slope and hydrodynamics of the fluvial system channel of the river Ethiope (e.g. **Royse 1968; 1970; Ludwikows-Kędzia, 2000; Szmańda, 2002; Adiotomre et al., 2021; Kasim et al., 2023**).

4.4.2 Bivariate plots and sedimentary environments

Bivariate plots of mean size versus sorting (**Tanner, 1991**), median size against sorting (after (**Stewart, 1958; Moiola and Weiser, 1968**), and mean size (M_z) versus sorting (**Friedman, 1961; 1967; Moiola and Weiser, 1968**) were used for the diagnosis and reconstruction of the sedimentary environments and transportation modes of the sediments. **Tanner (1991)** proposed a bivariate plot of mean size versus sorting to decipher sedimentary environments (fields) such as fluvial and stream episode,

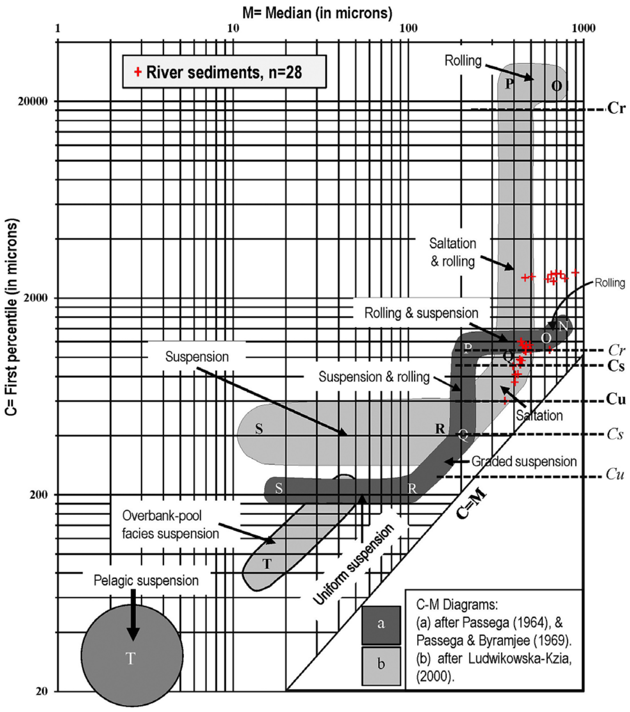

Figure 6: C–M diagrams of the transport mechanisms of river Ethiope sediment: (a) after **Passega (1964)**, and **Passega and Byramjee (1969)**, (b) after **Ludwikowska-Kędzia (2000)**

closed basin, and partially open estuary to restricted estuary. Different authors have applied such bivariate plots to infer fluvial processes for both ancient and modern-day deposits (e.g. **Parthasarathy et al. (2016), Baiyegunhi et al. (2017), Ghaznavi et al. (2019), Adiotomre et al. (2021), and Kasim et al. (2023)**).

On this plot, the sediment samples from the river Ethiope are all plotted in the fluvial and stream episode field (see **Figure 7a**). **Stewart (1958)** and **Moiola and Weiser (1968)** also proposed bivariate plots for sedimentary environmental reconstructions and processes associated with such environments. On a composite bivariate plot adapted from **Stewart (1958)** and **Moiola and Weiser (1968)**, the river Ethiope sediment samples were plotted mainly in the river section with the associated river processes, while five samples were plotted in the beach environment (see **Figure 7b**). Also, on a composite plot after **Friedman (1961, 1967**) and **Moiola and Weiser (1968)**, the river Ethiope sediment samples plotted on the river field of **Friedman (1967)**, **Moiola and Weiser (1968)** and mixed river or dune section of **Friedman (1961)** and in the river section of **Moiola and Weiser** (**1968**) (see **Figure 7c**). In all the plots in **Figure 7**, river environment/processes were inferred from the bivariate plots (**Mycielska-Dowgiallo and Ludwikows-Kędzia, 2011; Baiyegunhi et al., 2017; Ghaznavi et al., 2019; Kasim et al., 2023**). These bivariate plots and the Visher's cumulative frequency curves (see **Figure 5**) corroborate those of Passega's C-M plot (see **Figure 6**); thus suggesting that the sediments of the river Ethiope typify those of the fluvial settings where saltation, suspension, rolling-suspension, and suspension-traction process commonly prevailed.

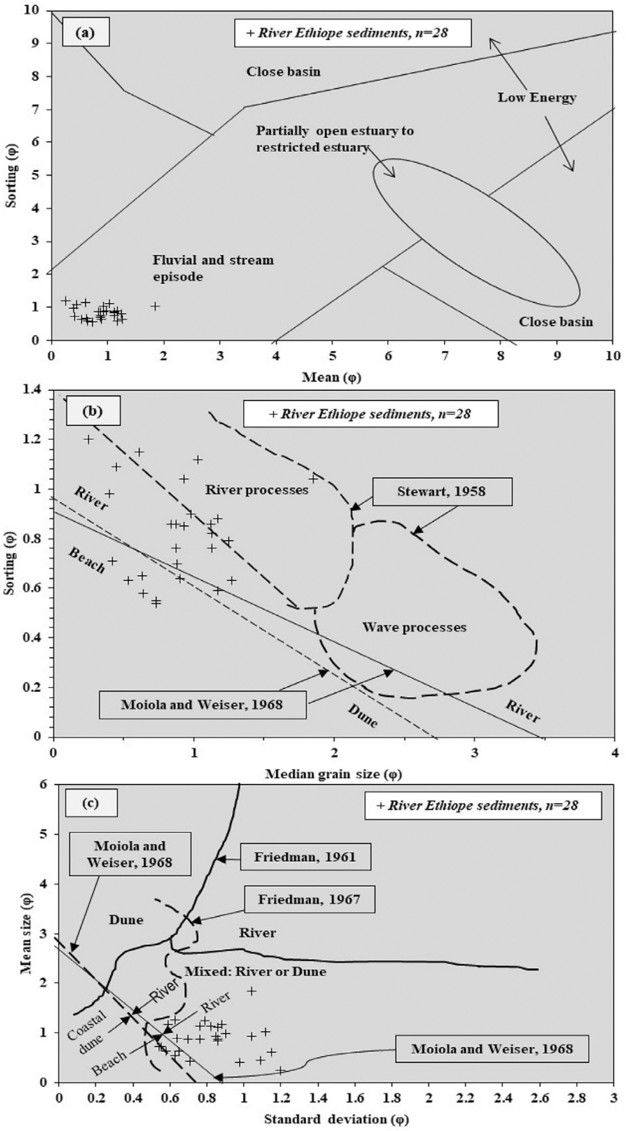

Figure 7: Bivariate plots for environmental diagnosis of river Ethiope sediments: (a) mean size (M_z) versus sorting (σ_i) (modified after **Tanner, 1991; Parthasarathy et al., 2016**); (b) median size versus sorting (σ_i) (modified after **Stewart, 1958**; **Moiola and Weiser, 1968**); (c) mean size (M_z) versus sorting (σ_i) (modified after **Friedman, 1967**; **Moiola and Weiser, 1968; Parthasarathy et al., 2016**).

4.5. Sedimentary Environments

The current study demonstrated some similarities in the textural characteristics of the modern sediments with those used by these authors (e.g. **Visher, 1967; Friedman, 1967; Moiola and Weiser, 1968**). According to **Friedman and Sanders (1978) and Selley (2000)**, the poorly sorted and the moderately-sorted sediments depicted sedimentation in a fluviatile environment. The sediment load of the river Ethiope is a combination of

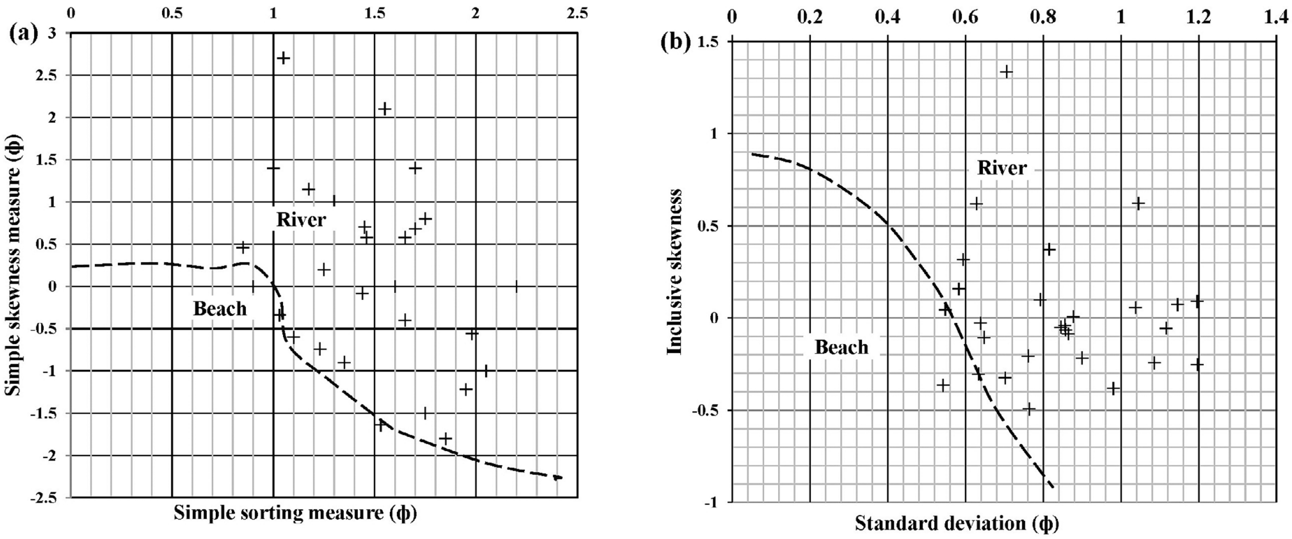

Figure 8: Bivariate plots for environmental diagnosis of river Ethiope sediments: (a) Simple skewness measure versus simple sorting measure; (b) Inclusive skewness against standard deviation (modified after **Friedman, 1967**)

Table 3: Summary of the computed Eigenvectors (V_1 versus V_2 and their depositional environments interpreted from the bivariate plot of the multivariate discriminant function of V_1 against V_2

Sample #	**V_1**	**V_2**	**Sedimentary Environment**	**Sample #**	**V_1**	**V_2**	**Depositional Environment**
SAP-1	2.28	2.40	River	UMT-2	3.15	2.93	River
SAP-2	1.94	1.59	Turbidite	UMT-3	1.65	2.11	Beach
AMK-1	1.46	0.19	Turbidite	OWH-1	2.59	2.86	River
IGN-1	1.99	1.41	Turbidite	OBN-2	2.73	2.48	River
EKU-1	0.88	0.58	Beach	OBK-2	2.22	2.36	River
ORA-1	1.97	2.16	River	ABK-2	1.70	2.17	Aeolian
ORA-2	2.11	2.80	River	ORA-3	3.81	5.28	River
ERH-1	1.62	1.15	Beach	EKU-2	1.81	1.67	Beach
ABK-2	1.65	1.51	Beach	OKP-1	3.86	5.23	River
UMG-2	2.05	2.64	River	AGH-1	4.69	7.33	River
OBK-1	1.90	1.86	Beach	AMK-2	2.95	4.33	River
OBN-1	2.26	1.68	Turbidite	SAP-3	1.84	2.82	Shallow Marine
EBD-1	1.76	2.02	River				
UMT-1	2.21	2.42	River	***Minimum***	**0.88**	**0.19**	
UMJ-1	0.98	0.48	Beach	***Maximum***	**4.69**	**7.33**	
UMJ-2	1.80	0.62	Beach	***Average***	**2.21**	**2.40**	**River**

Where: Sample # = sample number; V_1 = Eigenvector 1; V_2 = Eigenvector 2.

minor mud, high sand proportion, and few gravels. Some authors have reported such sediment loads as deposition in a river environment (e.g. **Friedman and Sanders 1978; Boggs 2009**). Bivariate diagrams based on statistical parameters (e.g. simple skewness measure versus simple sorting measure (see **Figure 8a**; **Friedman, 1967**); inclusive skewness against standard deviation (see **Figure 8b, Friedman, 1967**); mean size versus standard deviation (see **Figure 7c**; **Moiola and Weiser, 1968**); and mean size against graphic skewness (see **Figure 7b**; **Friedman, 1967**) have been applied in this study. These bivariate plots favoured deposition in a fluvial rather than a littoral setting (see **Figures 7** and **8**).

Following **Sahu (1983),** both Eigenvectors (V_1 and V_2; see equations 1 and 2) were computed by applying the statistical parameters (Mz, σ_1, Sk_1, and K_G) and tabulated for the sediments of the river Ethiope (see **Table 3**). A multivariate discriminant plot of V_1 versus V_2 (**Sahu, 1983; Parthasarathy et al., 2016**) was obtained for the sediments (see **Figure 9d**). The diagram suggests 54% river, 14% turbidite, 25% beach, 3.5% shallow marine and 3.5% aeolian environments (see **Figure 9d**; **Table 4**).

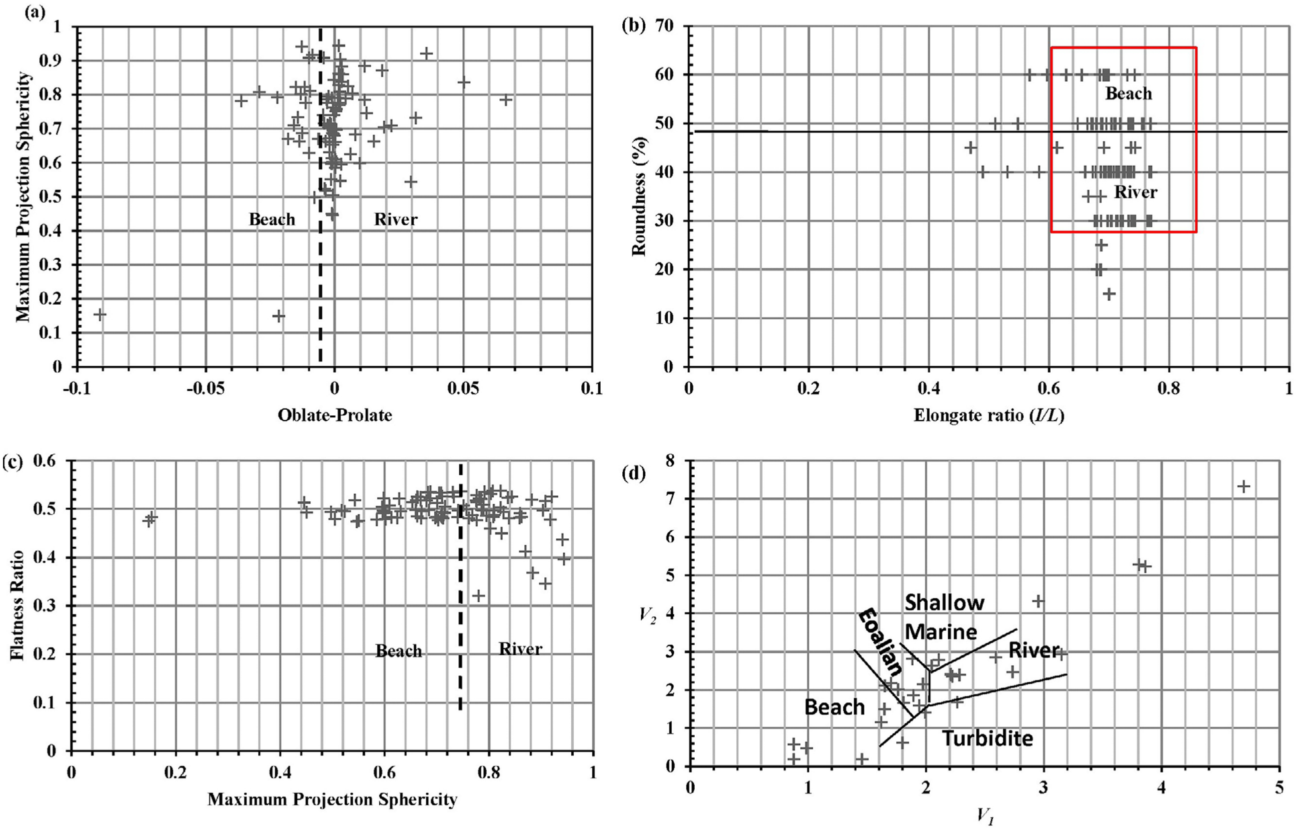

Figure 9: Bivariate plots based on the pebble morphometric analysis obtained for pebbles of the river Ethiope. (a) Plot of maximum projection sphericity versus oblate-prolate (after **Dobkins and Folk, 1970**); (b) Plot of roundness against versus elongation ratio (modified after **Sames, 1966**); (c) The plot of flatness ratio (FR) against maximum projection sphericity (after **Dobkins and Folk, 1970**); (d) Multivariate discriminant plot of Eigenvectors (V_1 versus V_2) (modified after **Sahu, 1983; Parthasarathy et al., 2016**).

Table 4: Summary of the Environment of Deposition interpreted from the pebble morphometric analysis for the pebbles of the river Ethiope

Morphometric Indices	Characteristics	Environment of deposition
Elongation ratio	Mean= 0.70	River
Flatness ratio	Mean= 0.50	River
MPSI	Mean value = 0.71	River
Oblate-Prolate	Mean value = 0.00	River
Roundness	Mean value = 42.20	River
Dominant pebble form	B = 22%, CB = 17%, C = 16%, CP = 16%, CE = 12%, P = 5%, E =5%, VB =3%, VP = 2%, VE = 2%	River
Bivariate plot of FR *vs* MPSI	75% River; 25% Beach	River
Plot of Roundness against ER	85% River; 15% Beach	River
The plot of MPSI *vs* O-P	84% River; 16% Beach	River

Where: *ER = Elongation Ratio; FR = Flatness Ratio; MPSI = Maximum Projection Sphericity Index; O-P = Oblate-Prolate; B = Bladed; CB = Compact-Bladed; C = Compact; CP = Compact-Platy; CE = Compact-elongated; P = Platy; E = Elongated; VB = Very Bladed; VP = Very Platy; VE = Very Elongated.*

Pebble morphometry has been applied as a palaeoenvironmental indicator for ancient clastic sediments (e.g. sandstone; **Odumodu and Ephraim, 2007**). The bivariate plots (maximum projection sphericity versus oblate-prolate, pebble roundness versus elongation ratio, flatness ratio against maximum projection sphericity) based on the pebble morphometry were also obtained (see **Figures 9a-c**). All the bivariate plots obtained for the pebbles of the river Ethiope suggested that over 75% of the pebbles were deposited by the river while less than 25% were in a beach environment. Pebble morphometric study of the sediment of the river Ethiope did not only suggest that the pebbles were transported as traction load but also deposited along the river channel (see **Table 4**).

5. Conclusions

In this study, hydrodynamic conditions, sediment transportation modes, and sedimentary environment were reconstructed based on the granulometric characteristics of the river Ethiope sediments.

The granulometric characteristics of the river Ethiope sediments revealed sands (medium to coarse), gravel, and mud in decreasing order of abundance. The sands are moderately-well sorted to well-sorted, strongly coarse skewed to strongly fine skewed, very platykurtic to extremely leptokurtic. The gravel-sized pebble forms are mostly bladed to compact-bladed, compact to compact-platy, compact-elongated and platy to elongated.

The presentation of grain size distribution data as cumulative frequency curves on a semi-log probability scale has enabled the evaluation of the sediments' hydrodynamics and transportation modes within the range of their straight-line sections. Thus, the river Ethiope sediments were transported through saltation, traction, and suspension. Also, the C-M patterns of Passega revealed rolling-suspension and saltation-rolling segments of transportation modes for the river Ethiope sediments. The sands, gravel, and mud were transported through saltation, traction, and suspension modes, respectively, and possible admixture of these transportation modes such as saltation/rolling and suspension/rolling.

The fluvial sedimentary environment (and the associated river processes) was inferred from the granulometric characteristics of the river Ethiope using bivariate plots (e.g. mean versus sorting, median size versus sorting), multivariant discriminant functions and Eigenvectors (V_1 and V_2). The results of pebble morphometry presented as bivariate plots (MPS vs OP, PR vs ER, FR vs MPS), morphometric indices (e.g. FI, MPS, OP), roundness, and the dominant pebble forms; most of these suggest fluvial environment for the river Ethiope sediments.

Although the discrimination of transport modes and sedimentary environment of river Ethiope sediments using granulometric analyses agrees with field observations and present-day sedimentary processes/environment operative in the study area, this approach is not without limitations or flaws. It should be noted that this work heavily relies on grain size analyses (mechanical sieving and pebble morphometry) as the sole means of diagnosing sediment transportation modes and sedimentary environment. Nevertheless, the use of other sedimentological parameters (e.g. facies analysis, primary sedimentary structures, sedimentary body geometry, palaeo-current pattern, fossil content, etc.), when available for studies, is essential in conjunction with grain size data for a robust determination of sedimentary environment.

Future research can, however, be carried out on the river Ethiope sediments, including thin-section petrography and bulk geochemical analysis of the sand deposits for the provenance study. Considering the importance of the velocity flow of a river, it is recommended that the flow velocity of the river Ethiope be measured using other more accurate tools such as the current meter and trajectory methods. This will help monitor the effect of any natural hazards on humans and the ecosystems.

This study offers valuable insights into the formation of fluvial sediments such as sands, gravel, and mud, which can ultimately transform into sandstones (and other related sedimentary rocks) in the Niger Delta Basin. These sandstones serve as ideal reservoir rocks for hydrocarbon accumulation and as reliable aquifers for groundwater. Additionally, the sand and gravel deposits found in the river Ethiope can be utilized as raw materials for various construction projects.

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SAŽETAK

Fluvijalna sedimentologija sedimenata rijeke Ethiope, delta rijeke Niger, južna Nigerija

Unatoč suvremenom napretku u proučavanju rijeka na globalnoj razini, preostaje mnoštvo istraživanja koje treba napraviti, posebno u području fluvijalne sedimentologije pojedinih današnjih riječnih sustava. Prethodne su studije o fluvijalnoj sedimentologiji sedimenata rijeke Ethiope (u južnoj Nigeriji) oskudne. Analitičke metode korištene u svrhu definiranja veličine zrna nužne su za donošenje zaključaka o hidrodinamičkim uvjetima siliciklastičnih sedimenata, načinima transporta i sedimentnim okruženjima. Dvadeset osam uzoraka (n = 28) sedimenata rijeke Ethiope odabrano je i proučavano korištenjem granulometrijskih analiza (sijanje i morfometrijska metoda). Rezultati granulometrijskih analiza pokazali su da se istraživani sedimenti sastoje od 82,75 % pijeska, 9,33 % šljunka i 7,92 % mulja. Ternarni dijagram pijesak–šljunak–mulj pokazuje da su sedimenti uglavnom predstavljeni šljunčanim pijeskom, dok nekoliko uzoraka upućuje na šljunčani pijesak, šljunčano muljeviti pijesak, muljeviti pijesak i pjeskoviti šljunak. Statistička analiza veličine zrna pokazuje da se sedimenti rijeke Ethiope sastoje od srednje do gruboga, slabo sortiranoga do umjereno dobro sortiranoga, jako grubo iskrivljenoga do jako fino iskrivljenoga te vrlo platikurtičnoga do izrazito leptokurtičnoga pijeska. Morfometrijska analiza valutica otkrila je da se valutice pojavljuju u raznim oblicima, u obliku oštrica (B) 22 %, kompaktnih oštrica (CB) 17 %, kompaktno (C) 16 %, kompaktno pločasto (CP) 16 %, kompaktno izduženo (CE) 12 %, pločasto (P) 5 % i izduženo (E) 5 %. Integracija bivarijantnih dijagrama, ternarnih dijagrama i C-M uzoraka iscrtanih za sedimente rijeke Ethiope uputila je na fluvijalno okruženje sa sedimentima koji su okarakterizirani niskom do umjereno visokom energijom koja prenosi sedimente različitih veličina i oblika poskakivanjem, vučenjem i suspenzijom. Ovo istraživanje također potvrđuje da su načini transporta sedimenta kao što su poskakivanje, vučenje i suspenzija tipični za riječna okruženja. Općenito, postojeći sedimentološki modeli izvedeni iz granulometrijske analize sedimenata i pomoću morfometrijskih metoda dobivenih iz današnjih rijeka mogu se primijeniti za bolje razumijevanje načina transporta, sedimentnih procesa i paleookoliša njihovih drevnih pandana.

Ključne riječi:
rijeka Ethiope u Nigeriji, fluvijalna sedimentologija, tekstura sedimenata, transport sedimenata, hidrodinamički uvjeti

Authors' contributions

Israel Aruoriwo Abiodun Etobro (1) (PhD, Senior Lecturer, Sedimentologist, Petroleum Geologist) the main contributor coordinated the sampling, grain size analysis, pebble morphometric analysis, and result interpretations. **Omabehere Innocent Ejeh (2)** (PhD, Associate Professor, Sedimentologist, Petroleum Geologist) provided the interpretation of the grain size analysis. **Glory Oghenevwede Ovwamuedo (3)** (M. Sc., Lecturer II, Environmental Geologist, Hydrogeologist) assisted in the collection of samples and pebble morphometric analysis.