PREDICTING THE DEPOSITIONAL ENVIRONMENTS AND TRANSPORTATION MECHANISMS OF SEDIMENTS USING GRANULOMETRIC PARAMETERS, BIVARIATE AND MULTIVARIATE ANALYSES

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ABSTRACT

Grain size distribution and classes present in sedimentary rocks are responsive to the physical changes of the transporting media and the basin of deposition. Analyzing grain size data is germane in reconstructing the sedimentary processes including identifying the palaeoenvironment of deposition. Twenty-three (23) samples, mainly sandstones, collected within latitude 6°055'-6°059'N and Longitude 005°044'-005°053'E in the Anambra Basin, were subjected to granulometric analysis, where grain size parameters (mean grain size, sorting, skewness and kurtosis) sensitive to environmental conditions were calculated. These parameters were integrated with bivariate and multivariate analyses. Graphic mean (M_z) in the study area range from 1.1 to 2.27 ϕ with an average value of 1.7 ϕ, suggesting that grains are predominantly fine to medium; sorting range from 0.71 to 1.36 ϕ with an average value of 1.02 ϕ, suggesting sediments are moderately sorted; skewness range from -0.57 to 0.51 ϕ with an average value of 1.28 ϕ suggesting coarsely skewed to fine skewed with a predominating near symmetrical skewness and kurtosis range from 0.57 to 1.51ϕ, with an average of 1.28 ϕ suggesting a very platykurtic to leptokurtic character. Bivariate scatter plots of the grains size parameters predicted the environment of deposition as shallow marine. Multivariate analysis calculated from established functions suggested environments that range from beach (backshore) to shallow marine (subtidal). The integration of the granulometric parameters, bivariate and multivariate plots predict an environment that is dominated by high energy indicating that the sediments of the study area were deposited in shallow marine environment. In addition, the Visher and Passega's C-M diagrams characterized the transport mechanism of the sediments as predominantly by saltation although traction and suspension modes also play some roles.

Keywords: transportation mechanism, granulometric parameters, bivariate analysis, multivariate analysis

1 INTRODUCTION

The use of particle size distribution and the assemblages of heavy minerals in sedimentary rocks make it possible to effectively locate and make use of grain size distribution and essential minerals in predicting depositional settings and processes as well as sediment source [1]. The provenance of sediment material as well as the environment of deposition may be obtained from an analysis of the grain sizes present in the sediment studied. The basic property of sediments affecting their transportation and deposition is the grain size. Grain size analysis therefore gives important insights to sediment's provenance, transport history and depositional conditions [2,3,4].

The texture of sediment refers to the shape, size and three-dimensional arrangements (packing) of the particles that constitute the sediment or a sedimentary rock. Grain size distribution and classes in a clastic sedimentary rock is sensitive to the physical changes of the transporting media and the depositional basin. The reconstruction of sedimentary processes, the identification of depositional environment, presentation and analysis of grain size data are all fundamental to understanding the basin formation with a view to unravelling its petroleum potentials.

The Anambra Basin, of all the basins in Nigerian, ranks almost next to Niger delta as for its richness in hydrocarbon reserves. Substantial amounts of work have been done on the geology of the basin in area of petroleum and stratigraphy, however, little was done on the sedimentology, except for works of Nwajide [5] and Nwajide and Reijers [6]. There is therefore a need to further understand the facies properties and stacking pattern, particularly of the sandstone facies that serve as reservoir rocks in terms of textural parameters, such as grain size, sorting, transportation history, paleoenvironment of deposition and provenance. These parameters are the focus of this present study.

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Location of the Study Area

The study area is located within the latitude 6°055’-6°059’N and longitude 005°044’-005°053’E (Fig. 1). It is accessible by roads and footpaths. It belongs to the Nigerian tropical rain forest zone with evergreen tree vegetation.

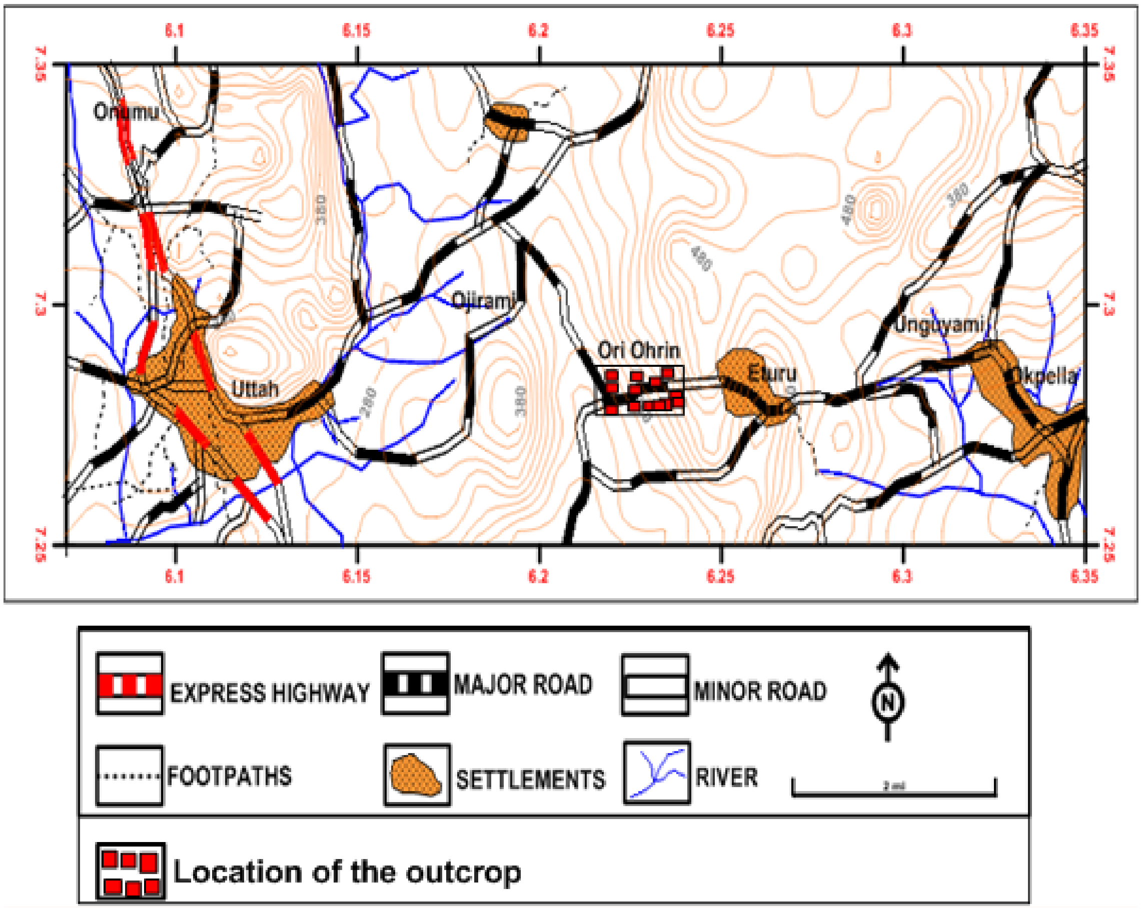


Fig 1: Location map of the study area showing sampling locations.

Basin Geology and Stratigraphy

Anambra Basin is a major inland sedimentary basin in Nigeria. Its evolution is explained by the separation of the African and South American plates during the Middle Mesozoic period [7]. The theory of Anambra Basin confirms that it contains Albian-Santonian sediments in the eastern half, referred to as Abakaliki depression, while the other half proto-Anambra was a platform with post Santonian sediments [5, 6, 8, 9, 10].

Anambra Basin is characteristic of Cretaceous and younger sediments [11]. Sedimentary rocks are formed by the accumulation of minerals and rock fragments of pre-existing rocks by weathering in the source area, followed by the transportation of these sediments to a depositional centre (basin). These transported sediments would later form siliciclastic sedimentary rocks (shale, siltstones, sandstones, or conglomerates) after undergoing compaction and lithification. The rocks have on them evidence of their depositional environment, transporting medium and original mineralogy. These evidences are reflected on the grain textures, sedimentary structures, and mineralogical composition which are used in characterizing sediments. The stratigraphy and lithostratigraphic units of Anambra Basin from the oldest to the youngest are as follows:

Nkporo Formation

The Nkporo Shale is the basal sedimentary unit deposited after the Santonian folding and inversion in Southeastern Nigeria and its Late Campanian in age [11]. The formation consists of marine shales, limestone lenses and sandstones [12].

The Enugu Shale

The Enugu Shale is limited to the central and northern parts of the Anambra Basin and consists of soft greyish blue or dark grey carbonaceous black shales and mudstones and coal, with interbeds of very fine sandstone/siltstone. It is associated with extensive syn-sedimentary deformational structures, such as faults [6, 11].

The Owelli Sandstone

The Owelli Sandstone containing medium to coarse grained feldspathic sandstone, regarded as facies of the Nkporo groups, is a lateral equivalent of Enugu shale. It is an elongated shoestring sand body to the northwest defining a meander belt of a fluvial channel system and a fluviatile point bar [11, 12].

Mamu Formation

The Mamu Formation is coaly. It conformably overlies the Enugu shale and contains sandstone, shale, mudstone, sandy-shale in various horizons [11].

Ajali Sandstone

The Ajali Sandstone overlies the Mamu Formation and is of a diachronous age from South to North (Middle-Upper Maastrichtian). Its thickness significantly varies from less than 300 m to over 1000 m in the centre of the basin [11]. The stratigraphy of the Anambra Basin is summarized in Figure 2.

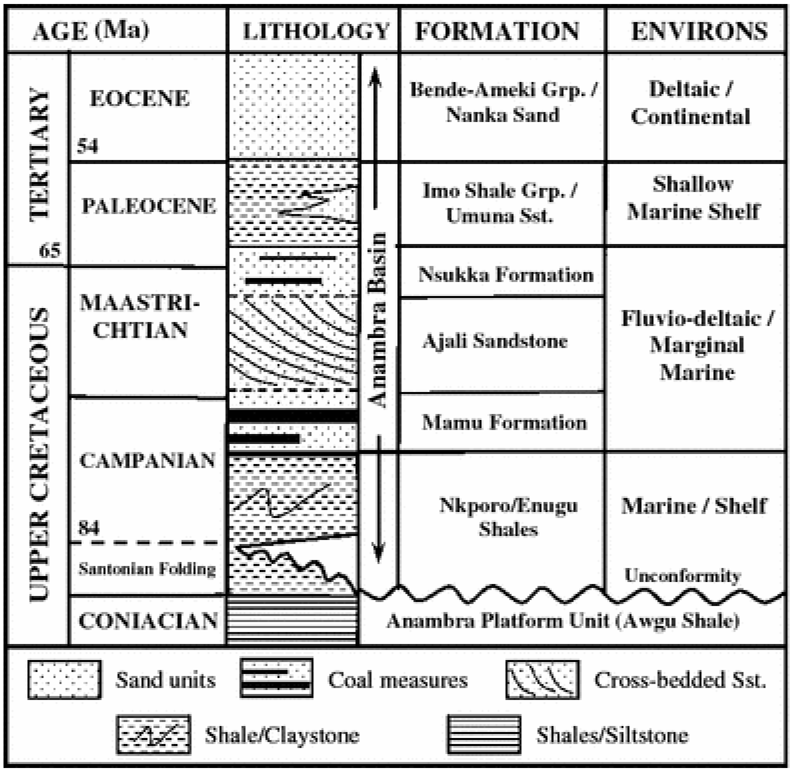


Fig 2: Lithostratigraphic succession in the Anambra Basin (according to [13, 14])

Methodology

The method employed in this study is the Granulometric analysis with bivariate and multivariate analyses incorporated. The field study involved observations of grains texture, colour, grains orientation, mineralogical composition, sedimentary structures and logging of exposed vertical sections, outcrop samples collection at intervals of 2.05m apart laterally and 0.5m vertically. In total, twenty-three samples were collected and subjected to granulometric analysis as described below.

Grain Size (Granulometric) Analysis

This involves the standard grain size analytical method whereby the samples were left to dry, disaggregate into individual grains and measuring of 100 g using sensitive weighing balance. Sieves of various sizes in "mm" such as 2.00, 1.18, 0.85, 0.60, 0.425, 0.3, 0.25, 0.15, 0.10, 0.075, 0.063 and pan were stacked on each other with the coarsest sieve size at the top and the smallest sized sieve size at the bottom; followed by the pan at the bottom of sieve 0.063 mm.

The weighted samples were individually put in the topmost (2.00 mm) arranged sieves, covered, clamped firmly in-place and placed on the Ro-tap automated shaker, switched-on and allowed to agitate for 15 minutes for each sample. The stack was then removed; the retained samples in each sieve and the pan were determined. Grain sizes percentiles were obtained and used to calculate the graphic mean, standard deviation (sorting), inclusive graphic skewness and graphic kurtosis for each sample.

The tabulated results from the sieved twenty-three samples are presented in Table 1.

The mass of the respective collected grains from the sieves were recorded and made use in the calculation of mean, sorting (standard deviation), skewness, kurtosis, bivariate and multivariate analyses were also carried out to properly characterize the environment of deposition. The discriminate functions (Y1, Y2 and Y3) of Sahu [16] were applied to the grain size data.

2 RESULTS AND DISCUSSION

Weighted samples data from the analyzed twenty-three samples are presented in Table 1. Granulometric results computed from the presented data in Table 1 were used to calculate grains parameters (Table 2) and their interpretation (Table 3).

Table 1: Statistical grain size analysis for all samples

Sieve (mm)	1a1	1a2	1a3	1b1	1b2	1b3	1c1	1c2	1c3	2a1	2a2	2a3	2b1	2b2	2c1	2c2	2c3	3a1	3a2	3a3	3b1	3b2	3b3
2	0.3	0.2	0.45	1.5	0.19	0.16	0.18	0.1	0.15	0.35	1.4	0.19	1.5	0.15	0.25	0.13	0.55	0.33	0.22	0.25	1.52	1.42	1.36
1.18	1.26	0.87	3.22	4.02	0.88	0.89	0.88	0.21	0.67	3.32	4.12	0.88	4	0.89	0.79	0.2	3.12	1.23	0.85	0.57	4	4.1	3.77
0.85	2.01	1.96	9.31	6.59	1.96	1.98	1.97	1.1	1.86	9.21	6.69	1.96	6.59	1.99	1.89	1.1	9.3	2.01	1.95	1.66	6.56	6.46	9.95
0.6	4.123	2.92	14.1	8.3	2.91	2.9	2.9	4.64	2.25	14.2	8.2	2.91	8.32	2.9	2.8	4.63	14.11	4.13	2.91	2.45	8.33	8.43	13.64
0.425	17.45	7.55	27.46	20.8	7.5	7.48	7.53	20.05	5.46	27.56	20.7	7.5	20.8	7.55	7.75	20.05	27.36	17.55	7.5	5.56	20.9	20.7	22.35
0.3	36.65	14.81	24.66	25.11	14.8	15	14.83	33.1	12.94	24.56	25.21	14.8	25.1	14.85	14.65	33.1	24.76	36.55	14.83	12.84	25.1	25.3	19.77
0.25	25.27	20.24	8.72	10.92	25.24	25.22	25.2	16.11	9.93	8.92	10.82	25.24	10.93	25.2	25.22	16.1	8.72	25.27	20.24	9.73	10.93	10.73	8.94
0.15	9.91	45	5.71	15.18	40.01	40.03	40.03	16.84	40.9	5.51	15.28	40.01	15.15	40	40	16.86	5.71	9.81	45	40.29	15.17	15.37	11.98
0.1	0.94	3.41	1.33	2.64	3.48	3.5	3.48	2.91	15.6	1.33	2.94	3.48	2.63	3.5	3.5	2.9	1.33	0.94	3.41	15.5	2.6	2.5	3.8
0.075	0.5	0.5	0.69	1.66	0.46	0.45	0.46	0.95	4.41	0.79	1.36	0.46	1.65	0.45	0.55	0.95	0.69	0.5	0.5	4.51	1.68	1.78	1.5
0.063	0.61	1.56	3.38	2.92	1.55	1.53	1.56	3.12	5.93	3.28	2.72	1.55	2.93	1.57	1.47	3.13	3.38	0.71	1.56	5.83	2.9	2.92	2.81
Pan	0.98	0.98	0.93	0.3	0.9	0.92	0.98	0.87	0.07	0.93	0.5	0.9	0.3	0.98	0.98	0.87	0.93	0.98	0.98	0.17	0.32	0.34	0.1
Total	99.02	99.02	99.07	99.92	99.94	99.94	99.02	99.13	99.93	99.07	99.92	99.94	99.92	99.02	99.02	99.13	99.07	99.02	99.02	99.93	99.62	99.66	99.87

Mean grain size (Mz)

This mainly defines the index of energy conditions during deposition. In general, the mean grain size, represented by the graphic mean M_z in the study area range from 1.1 to 2.27 ϕ with an average value of 1.7 ϕ (Table 2). It could be inferred from the average value of the graphic mean of grains that they are fine to medium sands.

Sorting (δ)

Inclusive Standard Deviation (sorting, δ) measure has an inverse relationship with standard deviation and defines the fluctuation of the energy of the sediments as they are transported to the site of deposition. Sorting values of the studied samples range from 0.71 to 1.36 ϕ, with an average value of 1.02 ϕ. The overall sorting is defined as moderately sorted (Table 2).

Skewness (S_K)

Graphic skewness measures the symmetry of the distribution. It shows whether the sediments are characterized by predominantly coarse or fine sediments. The skewness of the samples in this study range from -0.57 to 0.51 ϕ with an average value of 1.28 ϕ, suggesting that the samples were from coarsely skewed to fine skewed with a predominating near symmetrical skewness. Its average falls within the finely skewed range (Table 2). Graphic skewness for sediments changes from negatively skewed to positively skewed with high energy condition. Thus, the skewness values suggest a high energy environment of deposition.

Kurtosis (K_G)

It explains the sorting at the tails of the curve and relate them to the central portion. For the studied samples, its values range from 0.57 to 1.51ϕ, with an average of 1.28 ϕ, very platykurtic to leptokurtic character. The average being leptokurtic (Table 2).

Table 2: Calculated grains parameter for all samples

Sample Name	MEAN (M_Z)	KURTOSIS	SORTING	SKEWNESS
1a1	1.61	1.253976	0.493106	-0.2327
1a2	1.966667	1.324086	0.593182	-0.22167
1a3	1.116667	1.168033	0.806818	-0.18596
1b1	1.366667	1.168033	0.931818	-0.37368
1b2	1.95	1.288056	0.595833	-0.01216
1b3	1.966667	1.288056	0.583333	0.009091
1c1	1.933333	1.229508	0.543182	-0.07405
1c2	1.633333	1.437088	0.734091	0.19463
1c3	2.266667	1.457195	0.859848	-0.075
2a1	1.166667	1.229508	0.819318	-0.07971
2a2	1.1	1.168033	0.681818	-0.57368
2a3	1.99	1.513241	0.613636	-0.145
2b1	1.4	1.168033	0.906818	-0.25868
2b2	1.966667	1.346604	0.598485	-0.03043
2c1	1.95	1.4637	0.641288	-0.06125
2c2	1.666667	1.357249	0.686364	0.16902
2c3	1.483333	1.374156	0.544318	0.220241
3a1	1.883333	0.574293	0.783333	0.516364
3a2	1.933333	1.481715	0.606061	-0.25957
3a3	2.266667	1.479964	0.867424	-0.14423
3b1	1.416667	1.393443	0.977652	-0.14301

3b2	1.716667	1.168033	0.669318	0.335066
3b3	1.26	1.015681	0.936818	-0.02471
Average	1.696087	1.275986	0.716255	-0.06309

Bivariate Analysis

The granulometric parameters discussed above are used to make bivariate analyses plots in order to have a graphic view of how they relate to one another. This is done for the sole purpose of enhancing the interpretation of energy conditions, transportation medium and mode of deposition.

The plot of graphic kurtosis on the ordinate against skewness on the abscissa (Fig. 3) indicate that most samples fall between the negatively skewed and near symmetrical, except for one sample falling in the platykurtic region. As observed earlier, sediments that have a skewness transit from negative to positive are characteristic of a high energy environment of deposition.

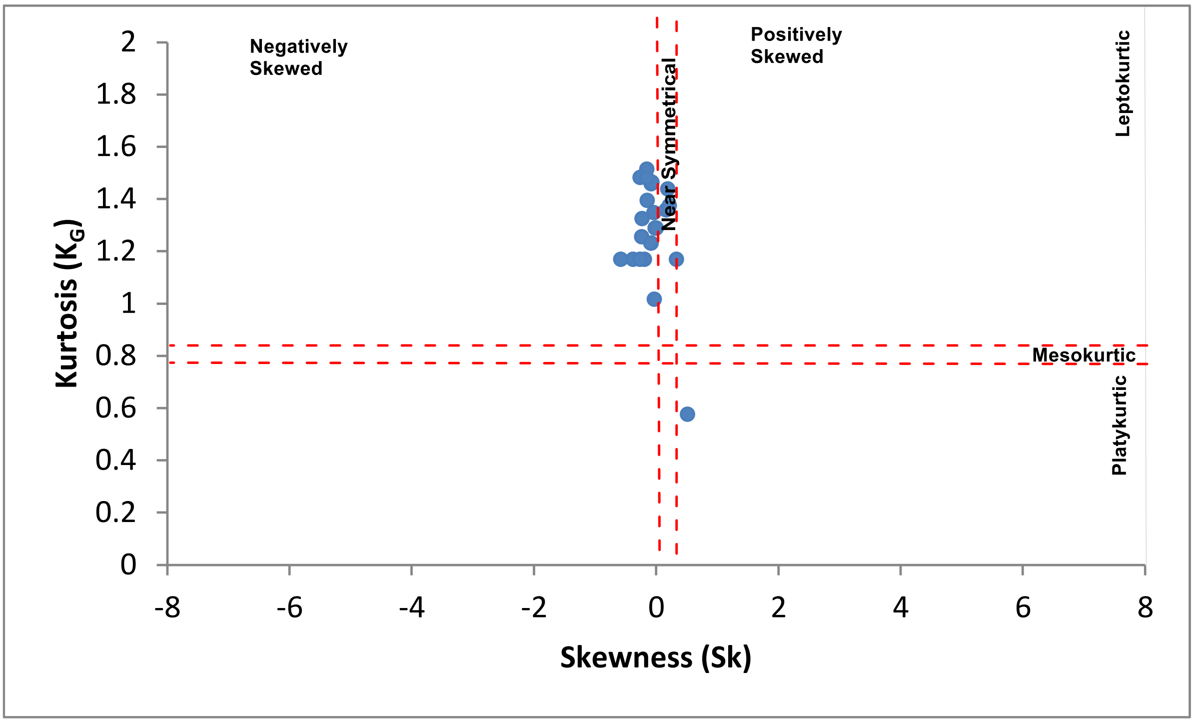
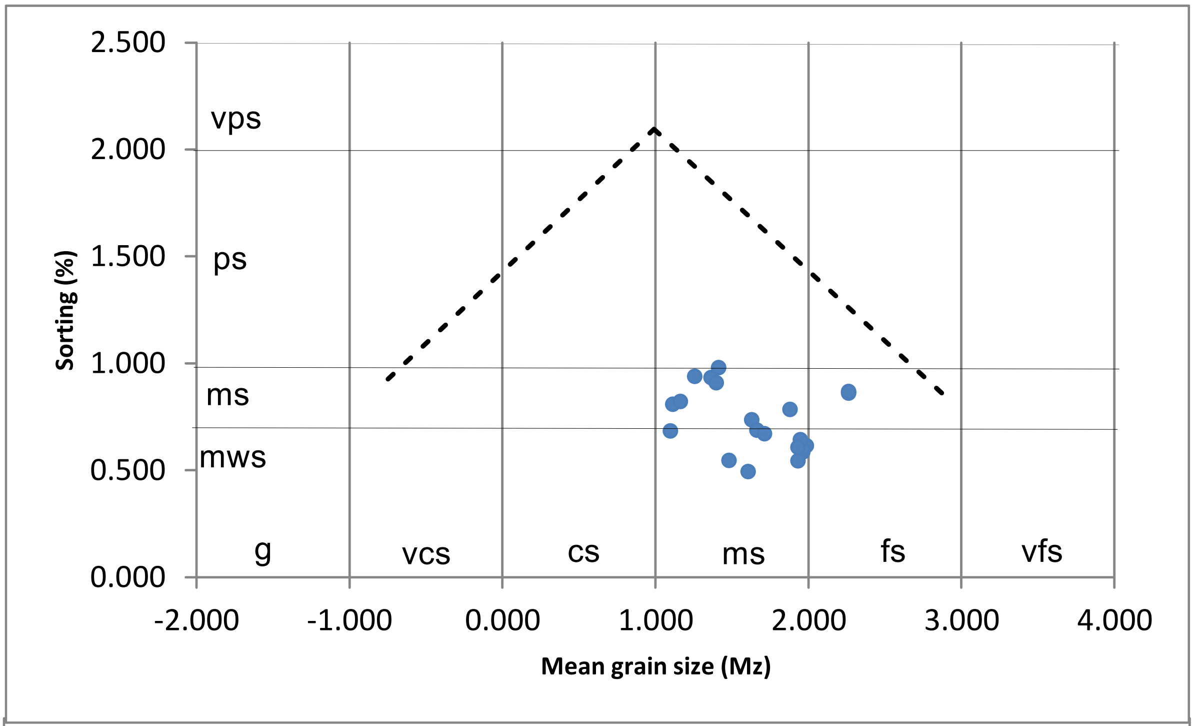


Fig 3: Bivariate plot of Kurtosis against Skewness (modified according to [15].

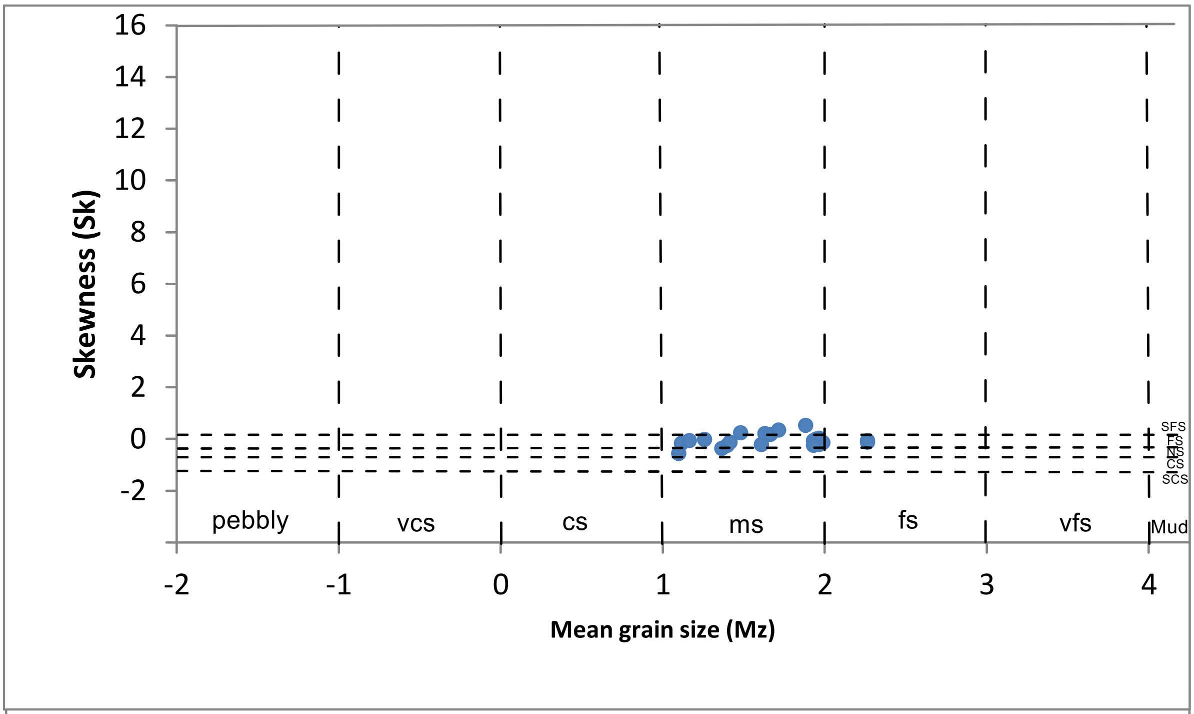
The plot between sorting and the mean grain size (Fig. 4) shows that the medium sand grains dominate the entire population of the samples. It also shows that sediments are moderately sorted to moderately well sorted. The plot further suggests that the variation in size classes was not too large. It is noteworthy that the plot of skewness against sorting (Fig.5) also points to the same depositional character and suggests a high energy environment dominating the study area.

The summary of the grain size parameters with the interpretations is as shown in Table 3.



vps-very poorly sorted; ps-poorly sorted; ms- Medium sorted; mws- moderately well sorted; g-granule, vcs-very coarse sand; ms-medium sand, fs- fine sand; vfs- very fine sand

Fig. 4: Bivariate plot of Sorting against Mean (Mz) (prepared according to [2])



vcs-very coarse grain sands; cs-coarse grained sand, ms-medium grained sand,
fs- fine grained sand, vfs- very fine grained sand, scs- strongly coarse skewed,
cs- coarse skewed, ns- Near symmetrical , fs- fine skewed, sfs- stronly fine skewed.

Fig. 5: Plot of Skewness against mean grain size (modified according to [15])

Table 3: Summary of grain size parameters with their respective interpretation per location

SAMPLE NAME	KURTOSIS	SORTING	SKEWNESS
1a1	Leptokurtic	Well Sorted	Very Positive Phi Value/Fine
1a2	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
1a3	Leptokurtic	Moderately Sorted	Very Positive Phi Value/Fine
1b1	Leptokurtic	Moderately Sorted	Very Positive Phi Value/Fine
1b2	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
1b3	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
1c1	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
1c2	Leptokurtic	Moderately Sorted	Very Positive Phi Value/Fine
1c3	Leptokurtic	Moderately Sorted	Very Positive Phi Value/Fine
2a1	Leptokurtic	Moderately Sorted	Very Positive Phi Value/Fine
2a2	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
2a3	Very Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
2b1	Leptokurtic	Moderately Sorted	Very Positive Phi Value/Fine
2b2	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
2c1	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
2c2	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
2c3	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
3a1	Very Platykurtic	Moderately Sorted	Very Positive Phi Value/Fine
3a2	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
3a3	Leptokurtic	Moderately Sorted	Very Positive Phi Value/Fine
3b1	Leptokurtic	Moderately Sorted	Very Positive Phi Value/Fine
3b2	Leptokurtic	Moderately Well Sorted	Very Positive Phi Value/Fine
3b3	Mesokurtic	Moderately Sorted	Very Positive Phi Value/Fine
AVERAGE	Leptokurtic	Moderately Sorted	Very Positive Phi Value/Fine

Multivariate analysis

As discussed under the method, multivariate analyses were applied to the grain size data in order to characterize the depositional setting, i.e. backshore (beach), shallow agitated marine (subtidal), Aeolian, fluvial, etc. To do this, the discriminate functions of Sahu [16] are employed. To discriminate between beach and aeolian sediment, the function below used is:

$$Y1 = -3.5688M_Z + 3.7016\delta^2 - 2.0766\, S_K + 3.1135\, K_G.$$

Where Mz is the grain size mean, δ is Inclusive Graphic Standard Deviation (Sorting), S_K is Skewness and K_G is the Graphic Kurtosis.

If Y1 is less than -2.7411, Aeolian deposition is indicated, whereas if it is greater than -2.7411, a beach environment is indicated.

To discriminate between beach (backshore) and shallow agitated marine (subtidal) environment, the discriminate function applied is:

$$Y2 = 15.6534M_Z + 65.79091\delta^2 + 18.1071S_K + 18.5043K_G$$

If the values of Y2 is less than 65.360 beach deposition is suggested, whereas if it is greater than 65.3650, a shallow agitated marine environment is likely.

To discriminate between shallow marine and the fluvial environments, the discriminate function below used is:

$$Y3 = 0.2852M_Z - 8.7604\,\delta^2 - 4.8932S_K + 0.0482K_G$$

If Y3 is less than -7.419, the sample is identified as a fluvial (deltaic) deposit, and if greater than -7.419 the sample is identified as a shallow marine deposit.

The values of Y1, Y2 and Y3 and the depositional settings they represent are as presented in Table 3.

Plots of Y2 against Y1 (Fig. 6) and Y3 against Y2 (Fig. 7) are also presented in Table 4. Both plots show the environment of deposition inferred from the multivariate function discussed above. Y2 Vs Y1 plot inferred Beach (backshore)/shallow agitated marine (subtidal). Also, Y3 vs Y2 plot inferred shallow agitated marine (subtidal)/ backshore (beach). These two plots correlate with each other.

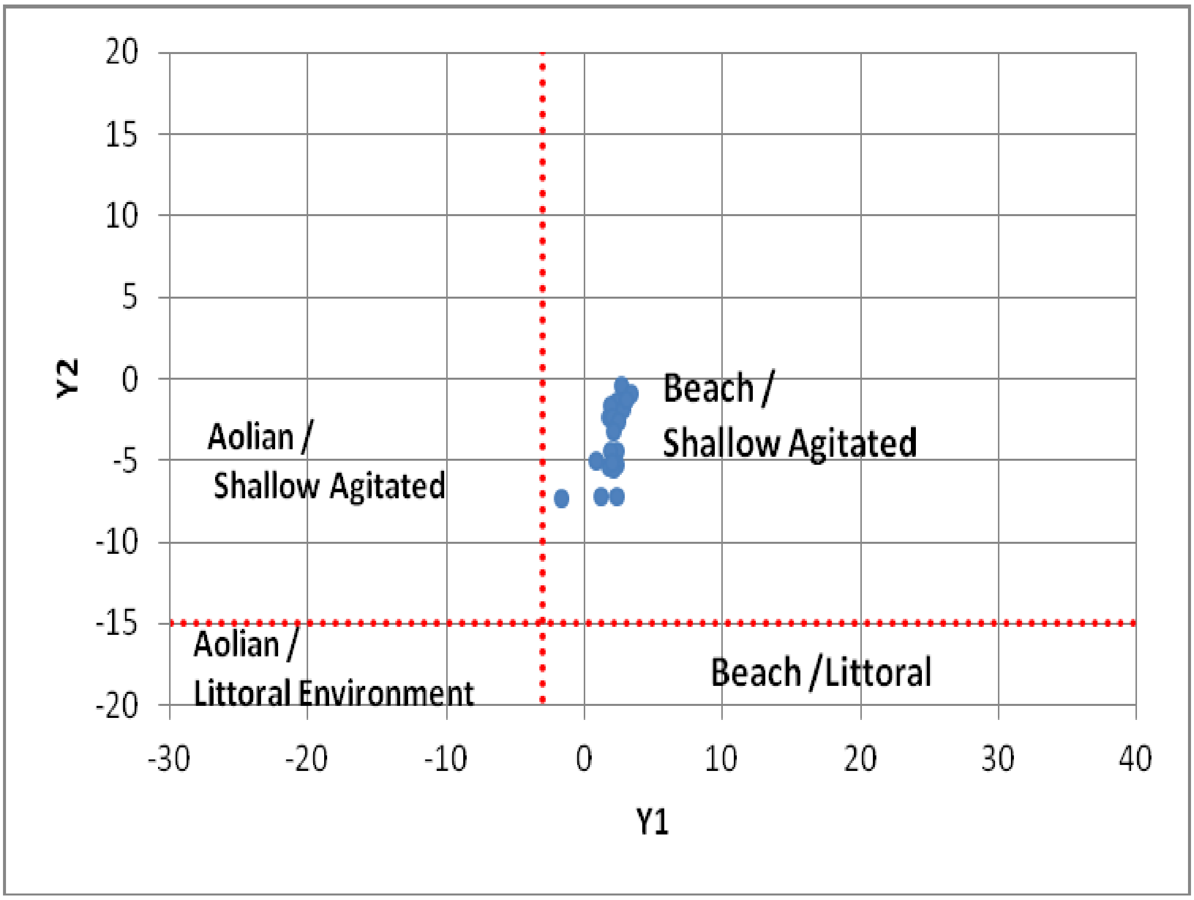


Fig 6: Multivariate plot between discriminant functions Y2 and Y1 showing the implied environment (according to [17])

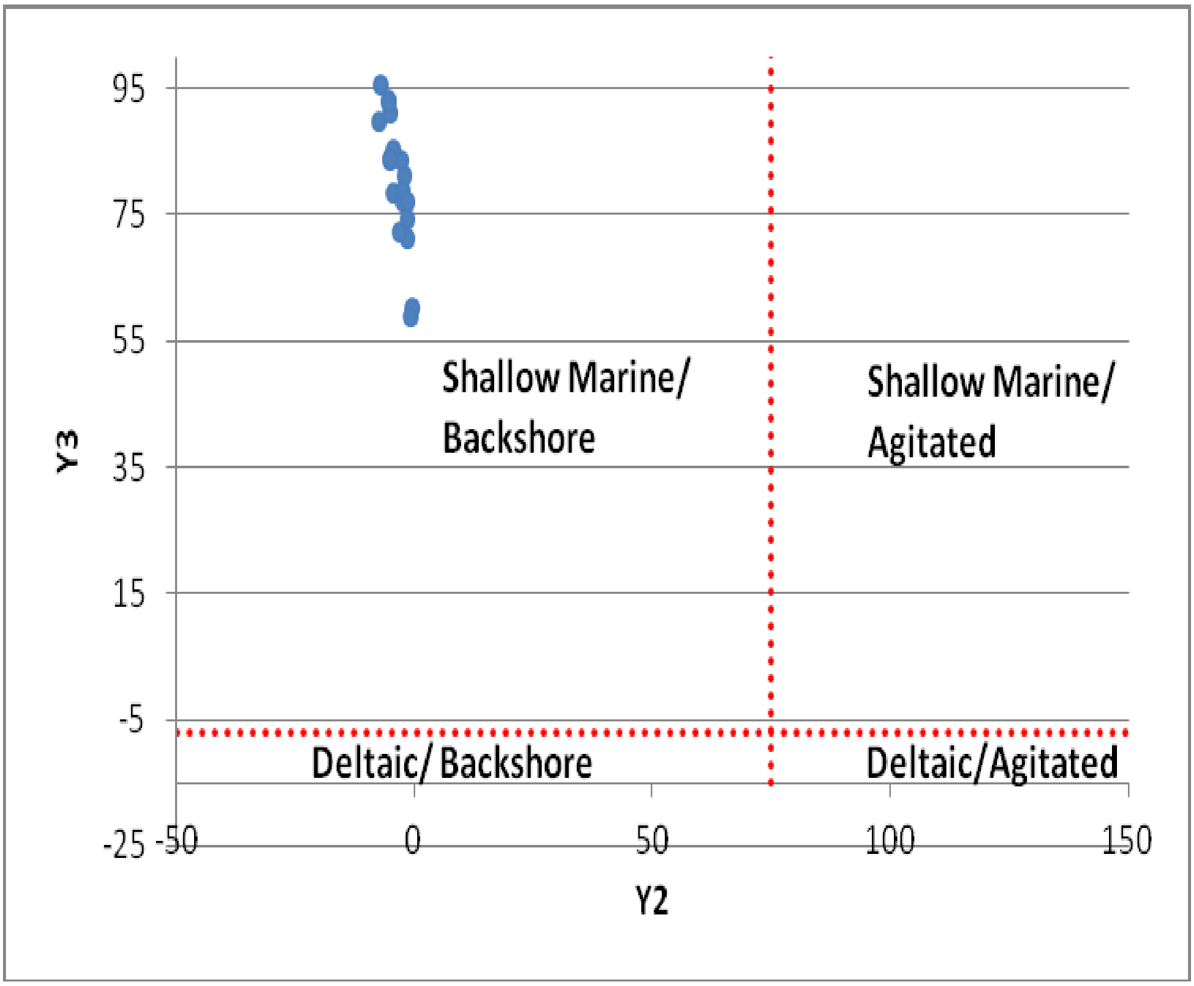


Fig. 7: Multivariate plot between discriminant functions Y3 and Y2 showing the implied environment (according to [17])

Table 4: Result of discriminate functions as calculated with the estimated environment for each sample

Sample Name	Y1	Y2	Y3	Y1	Y2	Y3
1a1	2.667118	-0.47189	60.16923	Beach Environment	Beach Deposition	Shallow Marine Deposit
1a2	2.397123	-1.37312	74.39248	Beach Environment	Beach Deposition	Shallow Marine Deposit
1a3	2.388023	-4.41793	78.49923	Beach Environment	Beach Deposition	Shallow Marine Deposit
1b1	2.310511	-5.33198	93.29396	Beach Environment	Beach Deposition	Shallow Marine Deposit
1b2	1.863395	-2.43239	77.46563	Beach Environment	Beach Deposition	Shallow Marine Deposit
1b3	1.81734	-2.40249	77.14277	Beach Environment	Beach Deposition	Shallow Marine Deposit
1c1	1.886261	-1.61176	71.06011	Beach Environment	Beach Deposition	Shallow Marine Deposit
1c2	2.030781	-5.13818	91.09298	Beach Environment	Beach Deposition	Shallow Marine Deposit
1c3	1.819515	-5.39327	109.6678	Beach Environment	Beach Deposition	Shallow Marine Deposit

2a1	2.288461	-5.09868	83.67897	Beach Environment	Beach Deposition	Shallow Marine Deposit
2a2	3.395907	-0.89535	58.99076	Beach Environment	Beach Deposition	Shallow Marine Deposit
2a3	2.778833	-1.94874	81.26814	Beach Environment	Beach Deposition	Shallow Marine Deposit
2b1	2.084334	-5.48251	92.87766	Beach Environment	Beach Deposition	Shallow Marine Deposit
2b2	2.063802	-2.36313	78.68707	Beach Environment	Beach Deposition	Shallow Marine Deposit
2c1	2.455972	-2.67634	83.52192	Beach Environment	Beach Deposition	Shallow Marine Deposit
2c2	1.869848	-4.4133	85.21897	Beach Environment	Beach Deposition	Shallow Marine Deposit
2c3	2.174267	-3.18397	72.10279	Beach Environment	Beach Deposition	Shallow Marine Deposit
3a1	-1.64837	-7.33737	89.77638	Beach Environment	Beach Deposition	Shallow Marine Deposit
3a2	2.984509	-1.32484	77.116	Beach Environment	Beach Deposition	Shallow Marine Deposit
3a3	2.021085	-5.16804	109.6954	Beach Environment	Beach Deposition	Shallow Marine Deposit
3b1	2.395799	-7.20226	108.1751	Beach Environment	Beach Deposition	Shallow Marine Deposit
3b2	0.909019	-5.01822	83.98849	Beach Environment	Beach Deposition	Shallow Marine Deposit
3b3	1.208804	-7.15921	95.738	Beach Environment	Beach Deposition	Shallow Marine Deposit
AVERAGE	2.007058	-3.81935	84.07043	Beach Environment	Beach Deposition	Shallow Marine Deposit

Log-Log Plot

Sahu [16] has shown that a log-log plot of mean phi-deviation of all samples on the ordinate (vertical axis) against the ratio of graphic kurtosis to mean size (M_z) times square of sorting (δ^2) of all samples along the abscissa (horizontal axis) (Fig. 8) gives the best separation between such processes and environment of deposition as turbidites, fluvial (deltaic), shallow marine, beach and aeolian.

This very plot (Fig.8) gives the exact environment of deposition of the sediments of the study as shallow marine.

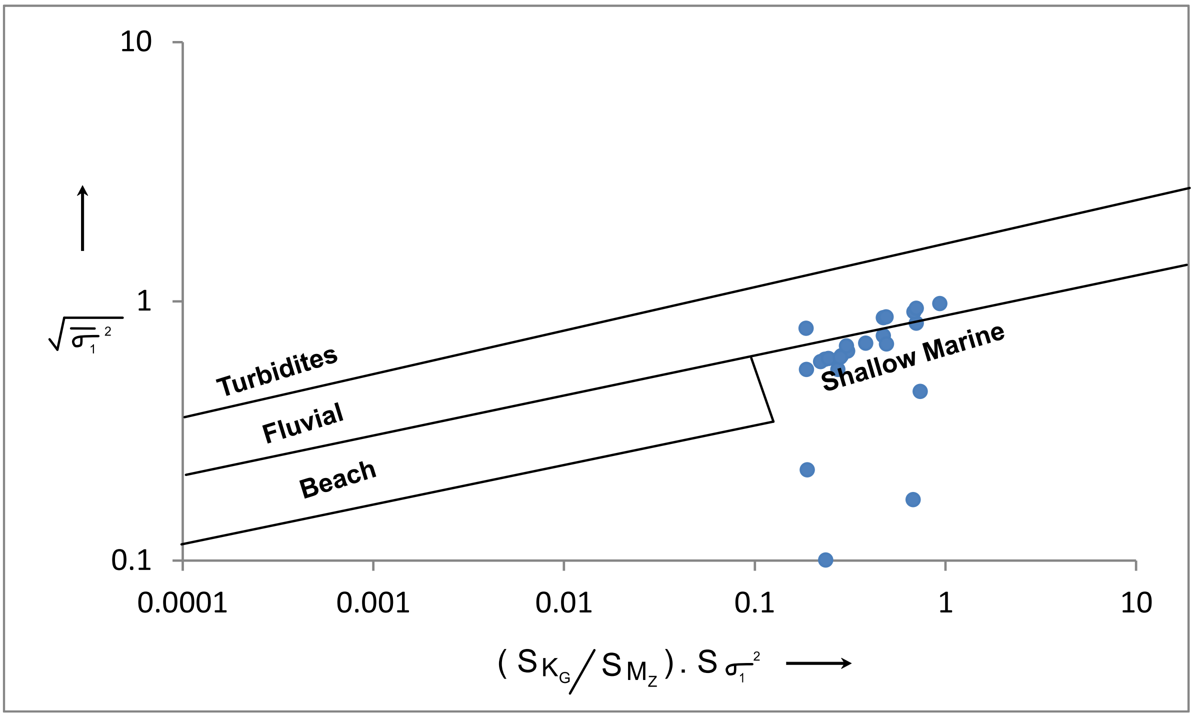


Fig. 8: Log-log plot showing general sedimentary environment of deposition of studied sediments (prepared according to [16])

Sediment transport mechanisms

Visher diagram

The log-probability curves suggested by Visher [18] was used to differentiate between the transport and hydraulic mechanisms of the sediments (i.e. traction, saltation and suspension). Visher plot for sediments of the representative samples (1a1, 2b2 and 3b3) of the area clearly shows the dominance of saltation transport mechanism over traction and suspension. Figures 9, 10 and 11 clearly show the Visher diagram for the representative sample indicated on each plot.

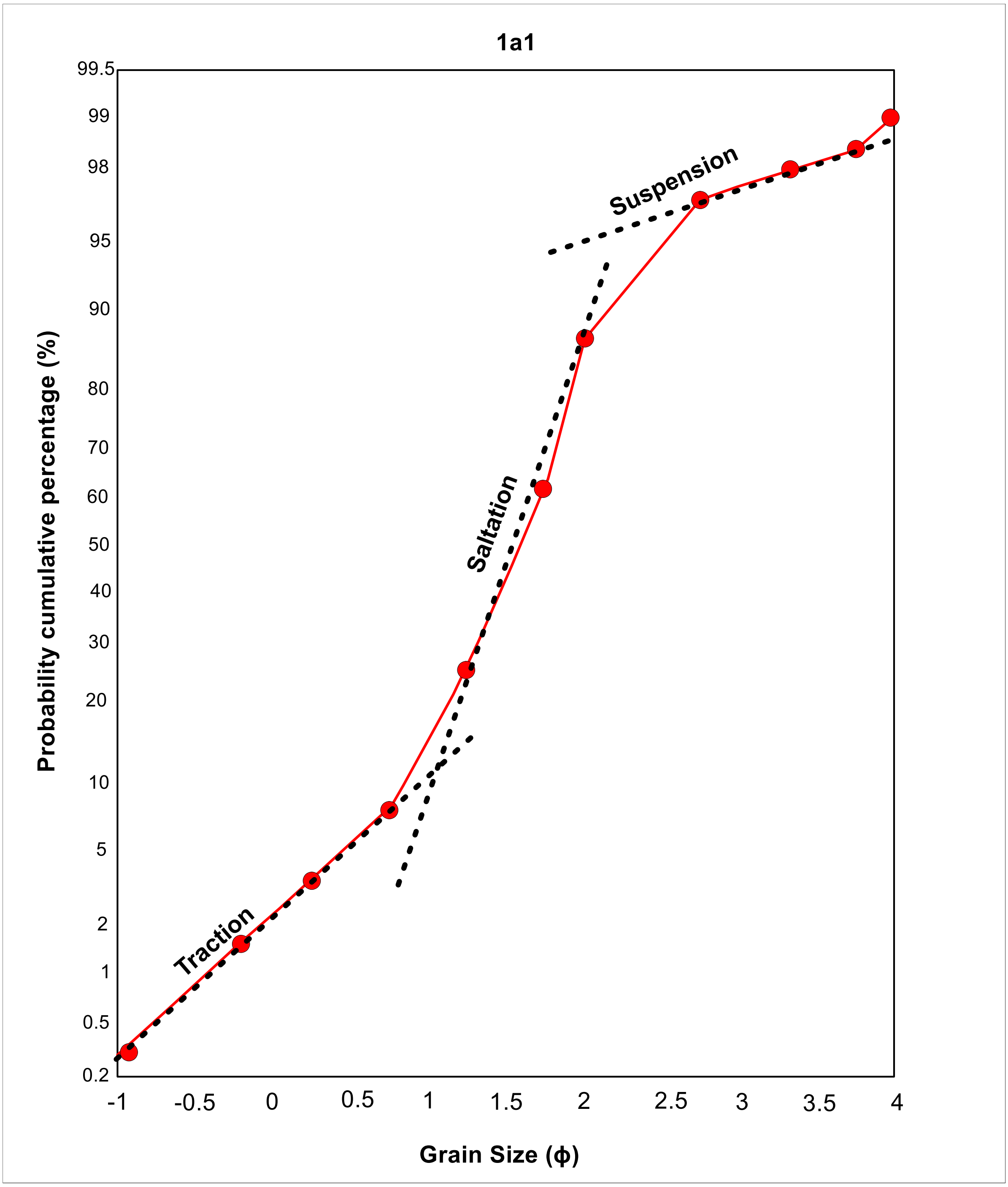


Fig 9: Arithmetic probability curve of sample 1a1 showing the sediment transport mechanism (according to [18])

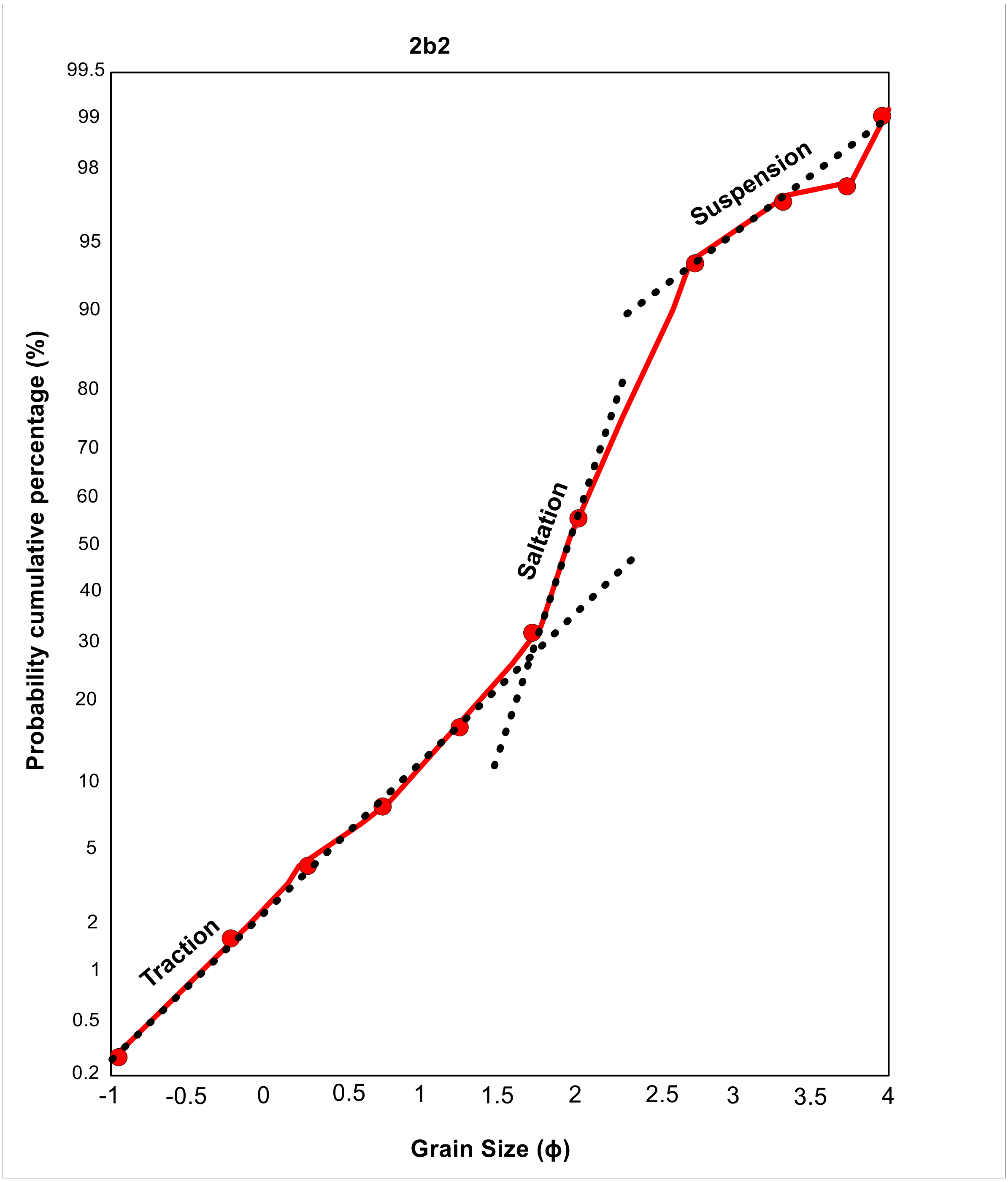


Fig 10: Arithmetic probability curve of sample 2b2 showing the sediment transport mechanism (according to [18])

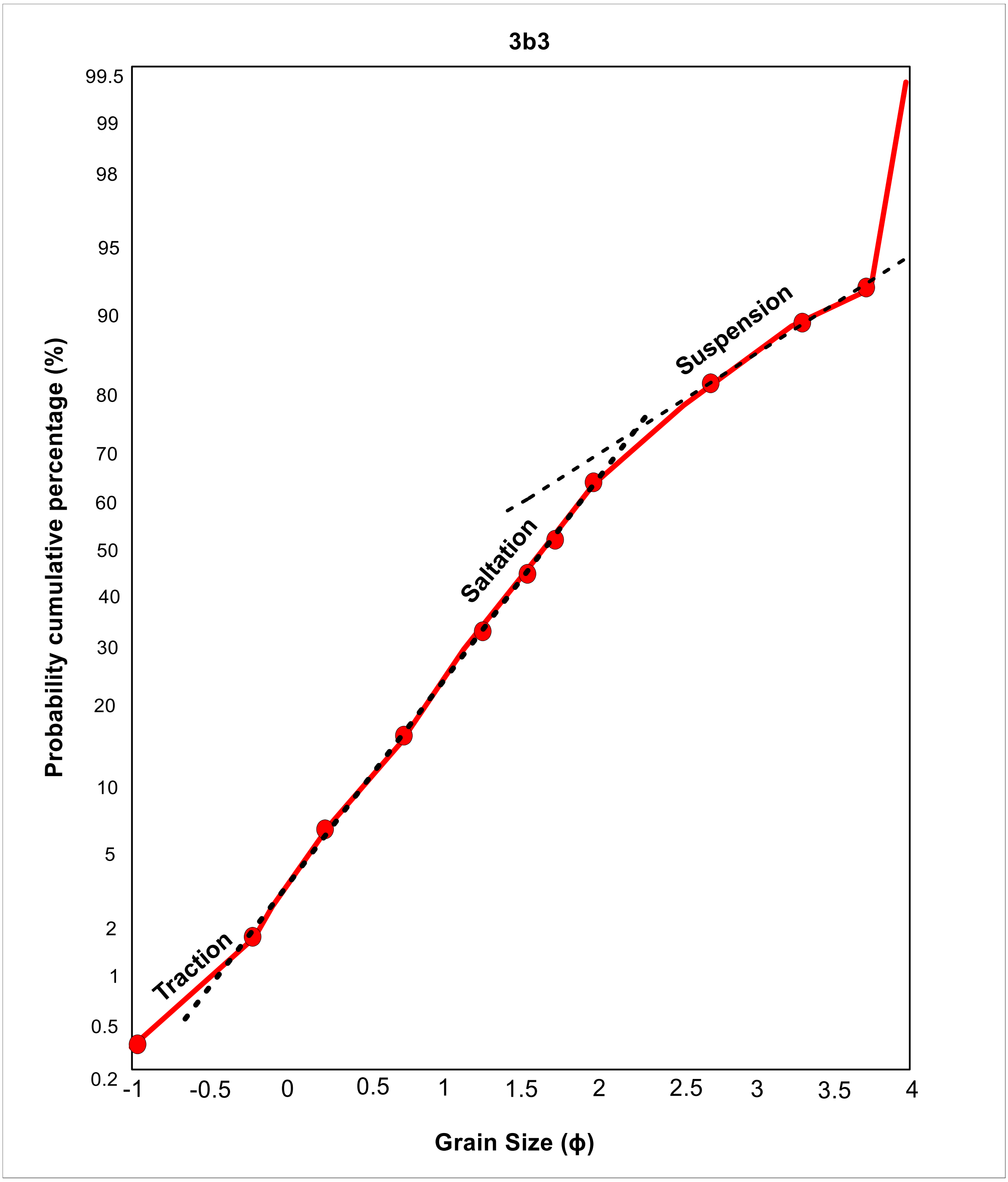


Fig 11: Arithmetic probability curve of sample 3b3 showing the sediment transport mechanism (according to [18])

The log probability curves (Figs. 9-11) indicate the variability of hydraulic depositional conditions for the studied sediments. Saltation is the major process of transportation of the sediments under investigated, although suspension and traction also played some role during their deposition. The sediments were mainly in saltation and suspension before being deposited.

C-M Diagram

The C-M diagram [19, 20] is another method to present the results from grain-size analyses, in which the values of the first percentile (C) are plotted against the median (M) (probability scale). The C and M values are presented in Φ units. To date, the Passega C-M diagram has been applied, in particular to the study of fluvial and coastal deposits. This is because both consist of different lithofacies, which can be 'translated' into depositional sub-environments with the help of the diagram. Different transport and depositional histories can thus be distinguished [21, 22].

Based on the works of Passega [19, 20] and Passega & Byramjee [23], the first percentile refers to the grain size that is representative of the maximum competence of the transporting medium. On the basis of the analysis of river and marine coastal deposits, Passega & Byramjee [23] distinguished three basic limits, viz. Cr (C- rolling), Cu (C- uniform suspension) and Cs (C-graded suspension). The Cr forms the lower size limit of grains transported through rolling (with a contribution of suspension); the Cs characterizes the maximum diameter of grains transported in 'graded suspension', i.e. mainly through saltation; and Cu is the limit for the maximum size of grains transported in homogeneous suspension, i.e. in the upper part of the water column.

In the diagram (Fig. 12), characteristic sections indicative of different transport and sedimentation modes can be distinguished [23]. They include transport in a homogeneous suspension (SR), transport in 'graded suspension', transport mainly through saltation (RQ), transport through suspension with some rolling (QP), transport through rolling with a contribution of suspension (PO), transport exclusively through rolling (N), and settling from suspension in stagnant water (T).

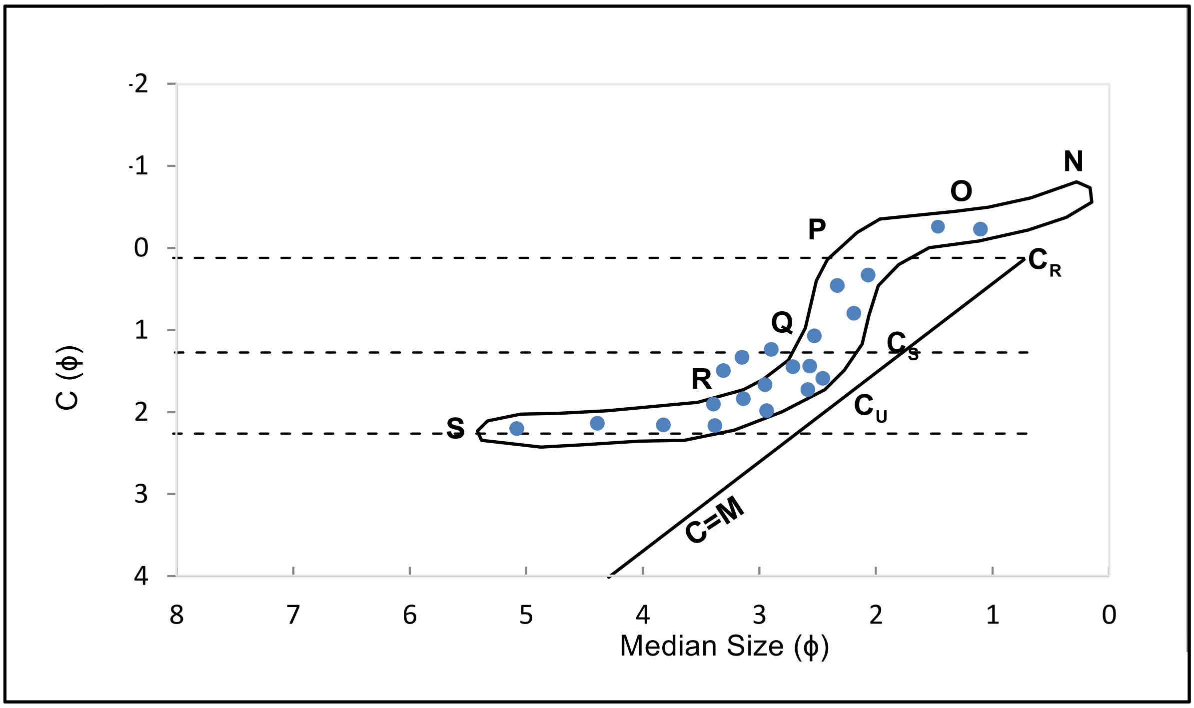


Fig 12: C-M plot showing the transporting mechanism of the sediments (prepared according to [19, 20])

Fig. 12 shows the majority of the samples plotted in the RQ region, which depicts that they are transported mainly by suspension, while others sparsely plotted in the ON (rolling) and SR (uniform/homogenous suspension) regions. The Passega C-M diagram agrees well with the earlier shown Visher diagram on the sediment transport mechanism.

3 CONCLUSION

As found from the characteristics of the sediments and the individual graphic and discrimination analyses carried out, it has been revealed that the analyzed sediments were deposited under the influence of an environment characterized by both shallow water agitation and beach, moderately sorted and high energy conditions. From the results presented, the sediments are likely to have been subjected to subtidal influence in a shallow marine environment. Therefore, the study area sediments depict energy regime associated with a high energy depositional process, moderate sorting, predominantly negatively fine skewness and leptokurtic in nature. Visher and Passega diagrams characterized the transport mechanism of the samples as predominantly by saltation although traction and suspension modes also play some roles.

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