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Grain Size Analysis, Textural Characterisation and Depositional Environment of Turonian Amasiri Sandstone, Southern Benue Trough, Nigeria

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Abstract
Grain size analysis of Turonian Amasiri Sandstone in southern Benue Trough has been undertaken to determine the controversial depositional environment of the formation. The formation was first studied on outcrops and 26 representative samples were collected and subjected to particle size analysis in line with standard procedures for dry sieving. Various methods of environmental interpretation of grain size distribution data were applied to constrain the depositional of the sandstones. The result indicates that the sands are medium and coarse-grained with mean size ranging from 0.15 to 1.87φ and averaging 0.96 φ. The sandstones are moderately to poorly sorted with standard deviation values ranging from 0.72 to 1.38 φ and averaging 1.07 φ. They exhibit a wide range of distribution from strongly coarse skewed to strongly fine skewed with skewness values ranging from -2.31 to 1.52 φ and averaging -0.04 φ but indicate a narrow range of kurtosis from mesokurtic to leptokurtic distribution with values ranging from 0.99 to 3.49 φ and an average of 2.06 φ. The sediments have bimodal with minor polymodal and unimodal distribution with primary modal size of 1.2 φ. The bivariate plots of size statistical parameters indicate fluvial environment of deposition. However, linear discriminant function analysis and the interpretations of log-probability plots indicate deposition in a fluvial, beach, and shallow marine settings, and thus suggesting a possible deposition in high-energy transitional environment. The C-M pattern of the samples indicates that sediments were transported mainly by rolling and suspension with subordinate fractions moved by rolling as well as suspension. Thus, it is deduced that Amasiri Sandstone was deposited in fluvial, beach, and agitated shallow marine environments.

Introduction

The Benue Trough of Nigeria is a NE trending and linear rift basin (Fig. 1) holding significant petroleum resources. From the Gulf of Guinea to Chad basin, it averages roughly 800 km in length and 130 km in width [1]. Amasiri Sandstone is the only formation of the Turonian Eze Aku Group that is composed mainly of sandstone facies with implications for groundwater aquifer and potentials for petroleum reservoir rock within the study area [2]. The formation occurs as a series of NE-SW trending prominent sandstone ridges with shale facies occupying the inter ridge lows [3,4]. The sandstone ridges run subparallel to the axis of the trough. Previous studies on the depositional environment of the formation were based mainly on lithofacies analysis [3,5-7]. The depositional setting of the formation is controversial as various authors have reached differing conclusions [6]. Based on of ammonite content, [8] interpreted the depositional environment of the Eze Aku Shale, with Amasiri Sandstone, considered a member, as shallow marine. Murat [9] deduced a transgressive shallow marine depositional environment for the Formation. Banerjee [3] described the Amasiri Sandstone as a shallow marine tidal to subtidal deposit, whereas [6] and [7] deduced that the formation is a mixed tide and storm, shallow to outer shelf deposit. Okoro and Igwe [6] reported a wide range of depositional environments ranging from the shallow shoreline through the shelf to submarine turbidite fan for the unit. In a separate study, AJaegwu et al [10] interpreted the Amasiri sandstone facies as turbidite fan deposits, suggesting deposition in a deep marine setting.

The textural characteristics of clastic sedimentary rock are product of the transportation history, depositional environment and the diagenetic histories [11,12]. An environment of deposition is one of the most important primary factors controlling the texture (grain size and sorting) of clastic sedimentary rocks as well as reservoir geometry, heterogeneity and diagenesis [13,14]. Post depositional processes may play a secondary role. Therefore, a good understanding of depositional environment can enhance geological and petro physical data for better exploration and production and thus reduce risks [15]. Grain size analysis is a veritable tool extensively used by sedimentologists and petroleum engineers for the determination of depositional environments and interpretation of geologic history, the geomorphic setting of a basin, tracing sediment provenance, mode of transportation and the hydrodynamic conditions at the site of deposition of detrital sediment [12, 16-22]. The grain size of clastic sediment is directly linked to the energy at the depositional site. Grain size and sorting are among the most important physical properties of sediment as they determine derived petrophysical properties of porosity and hydraulic conductivity of clastic reservoir rocks [23]. The use of grain size study in environmental analysis is hinged on the assumption that each sedimentary environment presumably exhibits uniquely different grain-size characteristics that distinguishes it from sediments deposited in other environments [11,12, 16,17,24]. An array of methods of interpreting depositional mechanisms and depositional environment of clastic sediments based on grain size

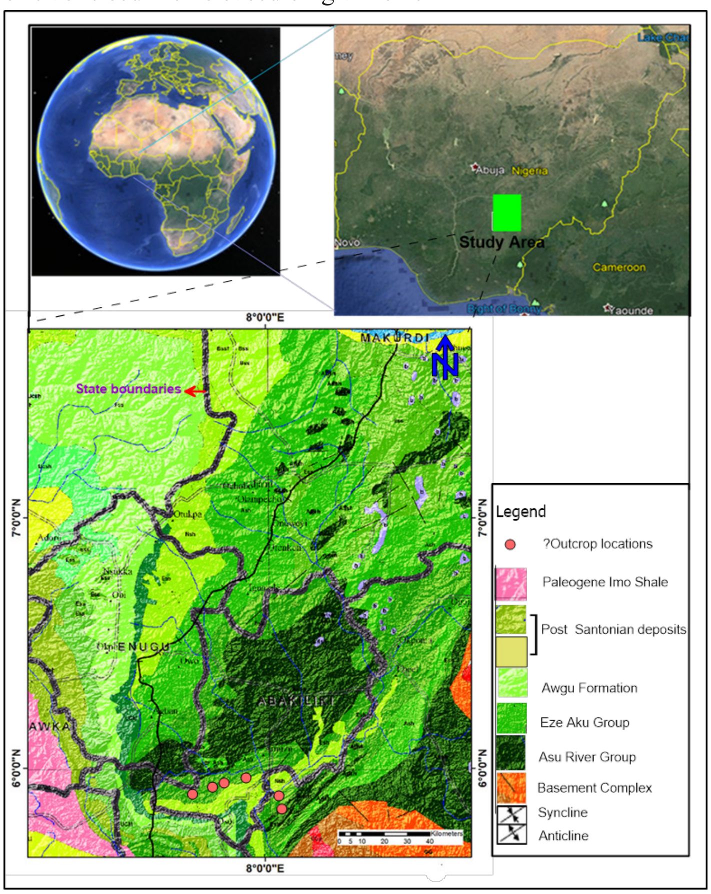

Figure 1: Modified geological map of the study area showing studied outcrop locations in Ugep, Itigudi, Afikpo, and Akpoha and environs (modified from Geological map of Nigeria, [25]

analysis data abound in literature, including bivariate plots of grain size statistical parameters, linear discriminant function analysis and analysis of the shape and nature of cumulative percentage log-probability plots. Despite the great potentialities in grain size analysis technique for environmental analysis, there is the paucity of researches applying the method to Amasiri Sandstone. It is in the light of the foregoing that this study on textural analysis is undertaken to establish the depositional environment of the formation.

Geological Setting of the Study Area

The study area is part of the southern Benue Trough in Nigeria which in turn is a segment of an extensive West African Rift System (WARS). Many researchers consider the trough as an aulacogen which originated as consequence of the separation of Africa and American continents in the early Cretaceous times [e.g. 26, 27, 28]. The basin is filled with over 5 km of deformed Cretaceous sediments and Cenozoic as well as volcanic rocks [29]. Sedimentation in the southern Benue Trough occurred during at least three major marine cycles [4,7, 28, 29]. The first marine incursion into the trough in the Albian resulted in the deposition of facies of Asu River Group composed mainly of shales on Aptian- Albian synrift sediments and pyroclastics that lies non-conformably on the Basement (Fig. 2). Sediments of Eze Aku Group and Awgu Formation were extensively deposited during the late Cenomanian-Turonian global marine episode [28, 29]. The initial cycle of sedimentation was truncated by mid Cenomanian compressive phase resulting in a depositional and erosional hiatus in the stratigraphic record [28-30]. The Eze Aku Group is comprised of Eze-Aku Shale, Nkalagu Limestone, and Igumale Formation, Amasiri Sandstone, and Konshisha River Sandstone. [27]. The Amasiri sandstone represents the uppermost part of the Eze Aku Group in Afikpo and its environs. Following the Santonian tectonic event, the Benue-Abakaliki basin was compressionally folded and uplifted and the depositional center shifted to the newly formed Anambra basin and Afikpo Syncline with subsequent deposition of post Santonian facies of Nkporo Group, Mamu, Ajali and Nsukka formations [7, 27, 28]. The last phase of sedimentation in Paleocene occurred mainly in the Cenozoic Niger Delta, resulting in the deposition of Imo Shale and Ameki Group.

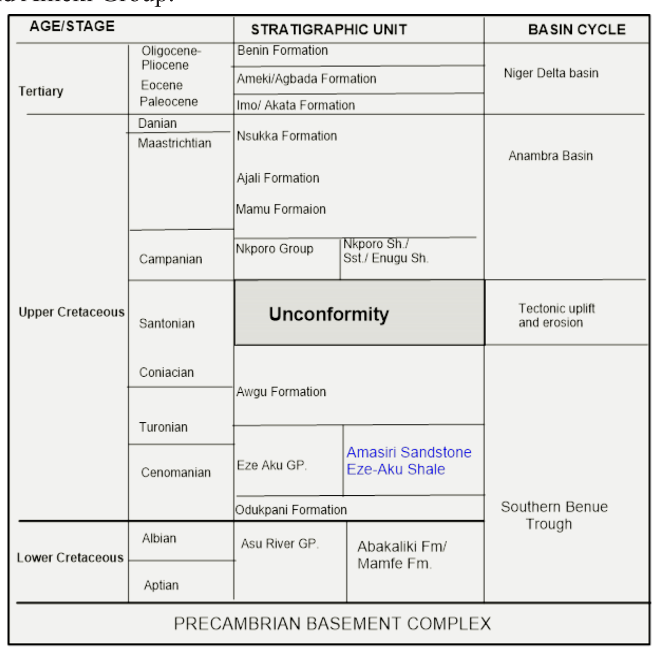

Figure 2: Stratigraphic framework of southern Benue Trough,

modified after [28].

Methodology

Twenty-six (26) poorly indurated and friable sandstone samples were collected from six outcrop locations comprising three samples from location 1, 2 samples each from locations 2, six from location 3, eight (8) from location 4, four from location 5, and tree from location 6 were subjected to particle size analysis. Care was taken to ensure that sample was not collected across beds as this can introduce error to the samples population. Mechanical sieving method using a Ro-tap Shaker was employed for the grain size analysis. About Precisely 100 g of each dry sample was pulverized. The disaggregated samples were thoroughly mixed and a representative fraction of the samples were obtained by coning and quartering technique. One hundred grammes (100.0 g) of each sample was sieved using a set of stacked sieves comprising 2000, 1180, 850, 425, 300, 150, 75, and 63 microns mesh sizes and a receiving pan. The analysis was performed in the Engineering Geology Laboratory of Applied Geology Department of the Federal University of Technology, Akure. The samples were introduced into the topmost sieve and then shaken by mechanical a Ro-tap shaker for 10 minutes. The fractions of grains retained in each sieve and the base pan were weighed and recorded. Plots of cumulative percentages and grain size frequencies plots were used calculate grain size statistical parameters. The inclusive graphic mean size, inclusive graphic standard deviation, inclusive graphic skewness and graphic kurtosis were computed using values read at the interceptions of the cumulative frequency curves at 5th, 16th, 25th, 50th, 75th, 84th, and 95th percentiles based on the formulae proposed by [31] as stated below:

Inclusive graphic mean $$M_z = \frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3} \quad (1)$$

Inclusive graphic standard deviation $$\sigma_I = \frac{\varphi_{84} - \varphi_{16}}{4} + \frac{\varphi_{95} - \varphi_5}{6.6} \quad (2)$$

Inclusive graphic Skewness $$Sk = \frac{(\varphi_{84} + \varphi_{16} - 2(\varphi_{50})}{2(\varphi_{84} - \varphi_{16})} + \frac{(\varphi_{95} + \varphi_5 - 2(\varphi_{50})}{2(\varphi_{95} - \varphi_5)} \quad (3)$$

Graphic kurtosis $$K = \frac{(\varphi_{95} - \varphi_5)}{2.44(\varphi_{75} - \varphi_{25})} \quad (4)$$

The relation $\varphi = -\log_2(D)$ where D is grain size in millimeter and φ is the grain size in Phi (φ) unit allowed conversion of grain size from millimeter to phi unit. Various combinations of grain size textural parameters including bivariate plots of standard deviation versus mean size and standard deviation versus skewness were used to constrain depositional environments.

Results and Discussion

On outcrop the sandstone facies used in the present study occur mainly as poorly indurated tabular beds with bed thicknesses varying less than 0.4 m to over 2.0 m. The coordinates of the outcrop locations from location 1 (L1) to location 6 (L6) as read from Global Positioning System (GPS) equipment are 50 54′ 27.0 ″ N and 70 54′ 15.9″ E, 50 50′ 00.7″ N and 8^0 05′ 26.9″ E, 50 55′ 57.2 ″ N and 8^0 01′ 28.9″E, 5^0 53′ 48.7″ N and 7^0 55′ 58.6″ E, 50 54′ 39.1 ″ N and 70 54′ 31.3 as well as 50 57′ 24.5 ″ N and 7^0 57′ 48.7″E (Fig. 1)The thickest beds were observed at the road cut at Itigidi (location 2 coded L2) where some bed thickness was observed to exceed 2.0 m (sample L4-S8). The sandstones beds from Locations 2 were marked by internal sedimentary structures namely parallel/wavy lamination, trough cross stratification, and graded bedding while those from location 4 displayed planar cross stratification, trough cross stratification parallel lamination and sigmoidal cross bedding.

The result of the grain size analysis (GSA) is presented in Table 1. The data is presented in a manner that reflect their stratigraphic position on outcrop section with L1, L2, L3 referring to outcrop location and S1 referring to the basal bed. The sandstone samples used for the analysis contained little or no fines (silt and clay fraction). The proportion of fines is highly variable. Generally speaking, the percentage of fines range from 0.00 to 6.14 % with an average of 0.89 %. Most samples have less than 1.00 % fines. Samples from location 1 have clay fraction ranging from 0.80 to 2.00 % with an average of 1.37 %. Those from location 2 have clay contents ranging from 0.6 to 1.30 % with an average proportion of 0.95 %. The highest amount of fines was associated with samples from location 3 with wide range from 0.4 to 6.16 and an average fines content of 2.14 %. The amount of fines in the samples from rest locations are quite low with values below not exceeding 1.0 %. This extremely low proportion of fine in the samples may suggest winning effect of waves.

Table 1: Grain size statistical parameters and coarsest 1 percentile of sandstone samples and their interpretations.

Samples	Mean size		Standard Dev.		Skewness		Kurtosis		C	Med.
	M_Z	Inter.	σ_I	inter	SK_I	Inter.	K_G	Inter.		
L1-S3	0.53	CS	1.16	PS	0.94	SFSK	2.28	VL	2297	707
L1-S2	0.58	CS	1.05	PS	0.82	SFSK	1.95	VL	2639	683
L1-S1	1.22	MS	0.96	MSo	0.37	SFSK	1.67	VL	2144	451
L2-S2	1.15	MS	0.87	MSo	0.39	SFSK	1.33	L	2219	457
L2-S1	0.36	CS	0.93	MSo	1.35	SFSK	1.74	VL	2297	785
L3-S6	0.47	CS	1.27	PS	1.13	SFSK	2.7	VL	2549	702
L3-S5	1.1	MS	1.38	PS	-1.14	SCSK	3.49	EL	2000	444
L3-S4	1.73	MS	1.24	PS	-1.74	SCSK	2.37	VL	2000	268
L3-S3	1.75	MS	1.26	PS	-1.63	SCSK	2.88	VL	1866	268
L3-S2	0.85	CS	1.36	PS	1.52	SFSK	3.46	EL	1866	574
L3-S1	1.87	MS	1.01	PS	-1.26	SCSK	1.71	VL	2928	250
L4-S8	1.12	MS	1.22	PS	0.22	FSK	2.27	VL	1866	435
L4-S7	1.1	MS	1.2	PS	0.23	FSK	1.95	VL	1932	420
L4-S6	0.47	CS	1.27	PS	1.13	SFSK	2.7	VL	3732	702
L4-S5	1.12	MS	0.99	MSo	-0.12	CSK	1.73	VL	2000	467
L4-S4	1.3	MS	1.08	PS	-0.34	SCSK	2.23	VL	3138	392
L4-S3	1.15	MS	0.99	MSo	0.01	NS	1.71	VL	3031	467
L4-S2	1.2	MS	0.92	MSo	-0.16	CSK	1.48	L	1803	435
L4-S1	1.25	MS	0.94	MSo	-0.2	CSK	1.5	L/VL	1866	420
L5-S4	0.75	MS	1.06	PS	0.56	SFSK	2.05	VL	3249	607
L5-S3	0.52	CS	0.87	MSo	-0.16	CSK	1.39	L	1741	697
L5-S2	0.22	CS	0.9	MSo	-0.52	SCSK	1.31	L	1778	812
L5-S1	0.52	CS	0.72	MSo	0.23	FSK	0.99	M	2297	707
L6-S3	0.9	MS	1.03	PS	-1	SCSK	1.79	VL	2549	500
L6-S2	0.15	CS	0.98	MSo	-1.00	SFSK	1.86	VL	2378	859
L6-S1	1.52	MS	1.25	PS	-2.31	SCSK	3.02	VL	1866	304

Note: CS –Coarse sand, MS – Medium sand, PS – Poorly sorted, MSo – Moderately sorted,SFSK - Strongly fine skewed, FSK – Fine skewed, SCSK – Strongly coarse skewed, CSK - Coarse skewed, NS – Near symmetrical, VL – Leptokurtic, L – Leptokurtic, M –Mesokurtic, EL- Extremely leptokurtic, C- Coarsest 1percentile, Med. – Midian size.

The result indicates that the mean size of sediments of Amasiri Sandstone exhibit a narrow range from medium (54 %) to coarse grained (46 %) distributed in nearly equal proportion with values ranging from 1.87 to 0.15 phi and with an average mean size value of 0.96 falling near the lower boundary of coarse sand class in the Udden-Wontworth grain size grade scale (Table 1). The coarsest sand came from location 6 (sample L6- S2) while the finest sediment was recorded at location 3 (SampleL3-S1). In all the outcrop locations except location 1 where the two samples are in the coarse sand class, the sediments mean size varies from medium to coarse-grained.

The standard deviation which measures the sorting of the sediments as well as indicates the fluctuations in the velocity of the depositing agent varies over a narrow range from moderately sorted (44 %) to poorly sorted (56 %) with values ranging from 0.72 to 1.38 φ and averaging 1.07 which signifies a generally poorly sorted sediment. The sediments from location 3 are generally poorly sorted whereas those from other locations are composed of mixtures of poorly sorted and moderately sorted sandstones.

The inclusive graphic skewness (SKI), measures the asymmetry of grain size distribution curve and indicates the position of the mean relative to the median (Boggs 2006)The degree of asymmetry of the grain size distribution have values which vary over a wide range from strongly fine-skewed, fine skewed, near symmetrical, coarse skewed to strongly coarse skewed, with values ranging from -2.31 (Strongly coarse skewed) to 1.52 (strongly coarse skewed) and with an mean skewness value of -0.04 φ indicating near symmetrical grain size distribution for the entire samples. The graphic kurtosis (KG) which measures the degree of flatness or peakedness of the grain size distribution curve.

Kurtosis values of analyzed samples vary greatly over a wide range from mesokurtic through leptokurtic and very leptokurtic to extremely leptokurtic with values ranging from 0.99 to 3.49 φ and with an average value of 2.06 φ, indicating a generally very leptokurtic for all the samples. Majority of the samples (96 %) have leptokurtic to extremely leptokurtic distribution. Only about 4 % have mesokurtic distribution. The leptokurtic nature of the curves indicates relatively better sorting at central portion of the distribution than at the extreme and peaks taller than that of normally distributed curve. The mesokurtically distributed samples have curves comparable to that of normally distributed curve.

The log-probability plots of grain size distribution data indicate that majority the samples are composed of two or three distinct lines segments (Fig. 4) representing the occurrence of two or three subpopulations which may suggest sourcing of sediments from more than one provenances area or fluctuations in the velocity of depositing medium (water). The major transportation mechanism is saltation as indicated in the Fig. 3 below. Few samples such as L1-S3 and L4-S5 have suspension line segment. On the other hand, sample L4-S1 has only one-line segment that indicates particle transportation by saltation. This distributional characteristic easily can be seen in the grain size frequency curves depicted in Fig. 3 as bimodal or polymodal patterns with most of the samples having similar major peaks (mode) at roughly 1.2 φ (medium sand) and a minor peak (secondary mode) at roughly 2.7 φ (fine sand) except for sample tL3-S3 that shows a reversal of this trend with a major peak situated at 2.7 φ and minor at 1.2 φ. Distinct polymordal pattern can be observed in the plot of sample L3-S2 in Fig. 3.

The log probability plots for the studied samples indicates the presence of 1 or 2 saltation populations as the major line segment (Fig. 4). The fraction of sediment originating from gravity settling of suspension load varies narrowly with values ranging from 0.5 to less than 0.8 % and corresponding to grain size of roughly 3.75 φ. Traction population is missing in most of the samples except for L3-S2, L6-S3 and L6-S2. The proportion of sediments transported by traction range from 20.0 to 46.0 % with a coincidental truncation point at 1.2 φ. The saltation populations range from -1.0 to 3.70 φ and in most cases, are characterized by gentle slope which indicates poor sorting. The proportion of the sediments transported by saltation is variable but range from about 56.0 to 100.0 %.

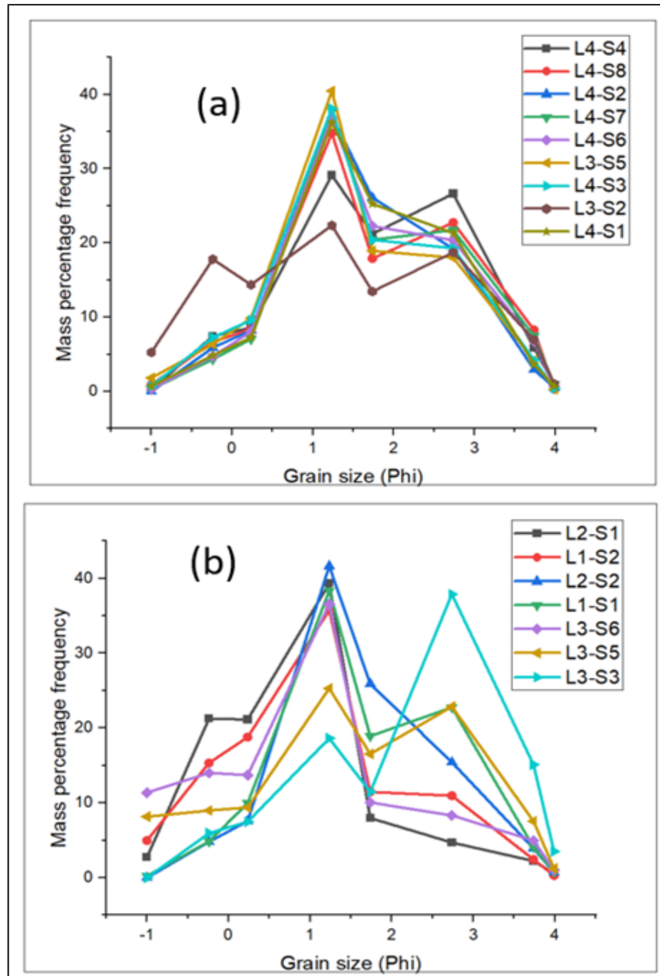

Figure 3: Frequency plots of grain size distributions. Note the position of primary and secondary modes.

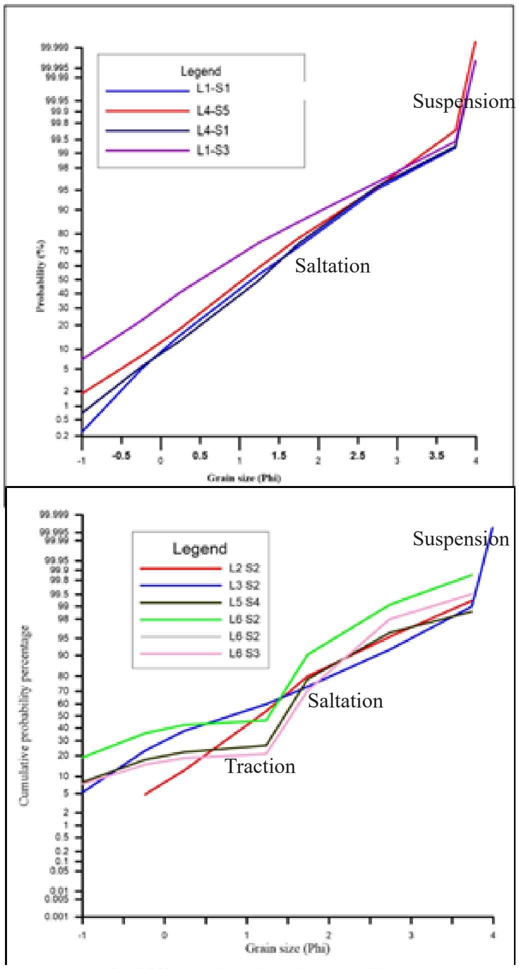

Figure 4: Log-probability plot for the studied samples. Note the dominance of saltation populations and minor well-sorted, suspension population in some of the sample

Depositional environment of Amasiri Sandstone
Grain size parameters

The use of grain size analysis data in deciphering depositional environment is based on the premise that different depositional environments is characterized by unique energy condition such that sand deposited in a particular depositional environment has a unique set of textural attributes that distinguishes it from those from other depositional settings [11, 23, 24, 33,34]. The mean size is of prime importance as it is one of the major determinant of hydraulic conductivity of sand and sandstone reservoir rocks [36]. The mean size has been found to have significant correlation with hydraulic conductivity. Knowledge of hydraulic properties of siliciclastic reservoir rocks is essential for ground water management of aquifers [35]. The observed graphic mean size range from medium to coarse-grained sandstone suggests moderate to high energy of depositional environments. The variations of the mean size over a narrow range suggests either minimal fluctuations in the velocities of the depositing agent or derivation of detritus from a single provenance source [21, 37]. The moderate to poor sorting may be associated with medium to carse grain size of the sediment. Folk and Ward [31] stated that best sorting of detrital sediment are to be found with fine to medium sands and that sorting gets worse with increasing grain size.

Standard deviation values indicates fluctuations in the kinetic energy regime and thus the velocity of the transportation medium prior to sediment deposition. The inclusive graphic standard deviation values range from 0.72 to 1.38 φ and with an average of 1.07 φ, suggesting that the sediments are comprised of 56 % poorly sorted and 46 % moderately sorted. This variations in sorting values may either suggest variations in the velocity of the depositing medium or mixing of sediments from different sources or mixing of sediments deposited by different transport mechanisms or absence of certain size ranges in the provenance [11, 12, 38]. Sorting and grain size exert primary control on permeability of reservoir rocks. Generally, permeability of reservoir material increases with better sorting or lower values of standard deviation. Sorting (standard deviation) can be used to distinguish between fluvial and beach/shallow sediments. According to [31], sorting values in the range of o.35 – 1.0 φ is indicative of fluvial sediment whereas sorting values of 0.25 to 0.5 φ indicates beach or shallow marine depositional setting. The overlap in the range of sorting values for various environments however makes it difficult to confidently separate the sediments on the basis of sorting alone. The moderate to poor sorting may suggests deposition in fluvial environment since fluvial sediments are characterized by moderate to poor sorting as the sediments cannot achieve good sorting in view of the limited available for sorting [37]. The poor sorting may suggest rapid rate deposition [24].

The wide range of skewness values from strongly coarse-skewed or negatively skewed to strongly fine skewed or positively skewed suggests huge fluctuations in the energy of the depositional environment. The negatively skewed distribution of some of the samples indicate the presence of excess coarse-grained detritus. Negative skewness values is attributed to winnowing of excess fines or mud by either wave and or current action and therefore suggests deposition in beach environment. According to [31], beach sediments are subjected to frequent reworking by wave and current actions which results in winnowing of the mud fractions. The highest energy in coastal setting is associated with foreshore beach where swash and backwash as well as current are effective in winnowing the clay fraction into deeper shelf area and concentration the coarse particles in the sediment. The positive skewness of the sediments indicate the presence of excess fines or absence of or minimal winnowing typical of fluvial deposition. Most fluvial sediments are positively skewed presumably as a consequence of rapid sedimentation rate with little or no time for winnowing. Other reasons including in situ weathering influence on sedimentary deposits can produce excess fine particles [23].

Bi- or polymodal distribution are usually either coarse skewed or negatively-skewed whereas those with unimodal distribution generally exhibiting symmetrical distribution. The calculated kurtosis indicates comparison of ratio of the sorting at the central part of grain size distribution to the spread at the tails. Friedman [33] stated that beach sediments are leptokurtic in character. Baiyegunhi et al [21] attributed mesokurtic and leptokurtic distribution to incessant supply of finer fractions to detritus after the winnowing action of the depositing agent and preservation of the original characters of the sediments during deposition.

Bivariate Plots of Statistical Parameters

Many authors have used the bivariate plots of various combinations of particle size statistical parameters to deduce the depositional environments of clastic sediments [31, 39, 34]. Stewart [40] and Ahmad et al [37] used bivariate plot of skewness against mean/median size to discriminate between river and wave processes. Friedman [33, 39] posited that the bivariate plots of mean size versus skewness and skewness versus standard deviation (sorting) can be used to discriminate between beach, dune and fluvial environments. Moiola and Weiser [34] used bivariate plot of mean size versus standard deviation to distinguish between river and beach sands as well as coastal dune and inland dune sands.

The binary plots of grain size statistical parameters are more useful environmental indicators than any single size parameter [31]. According to [34], the bivariate plot of mean diameter versus standard deviation is most effective in differentiating between beach, river sands and coastal dune sands. Thus the binary plots of three different combinations of grain size statistical parameters were employed to constrain the depositional environments of the sediments. The bivariate plot of mean size versus standard deviation based on [31] and [34] was applied to the current study to determine the depositional environment of Amasiri Sandstone (Fig. 5). The plot indicates that all

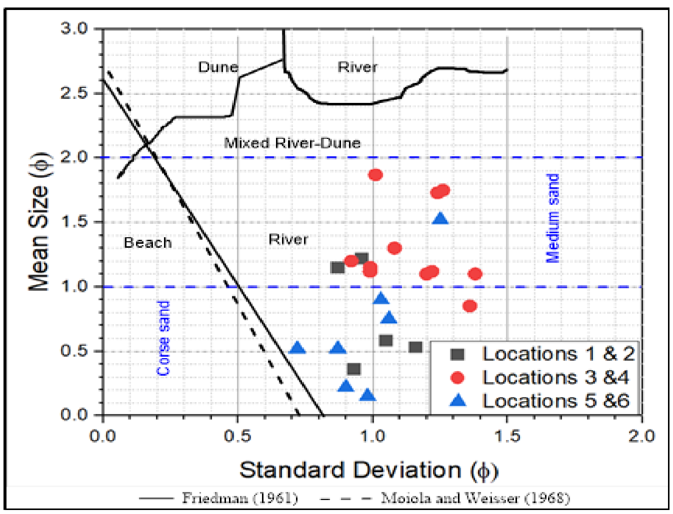

Figure 5: Binary plot of mean size versus inclusive graphic standard deviation, after [34] and [39].

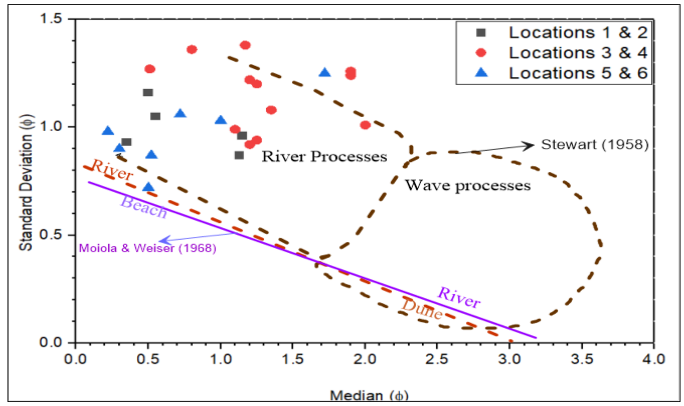

Figure 6: Binary scatter plot of inclusive graphic standard deviation versus median size, after [40] and [34].

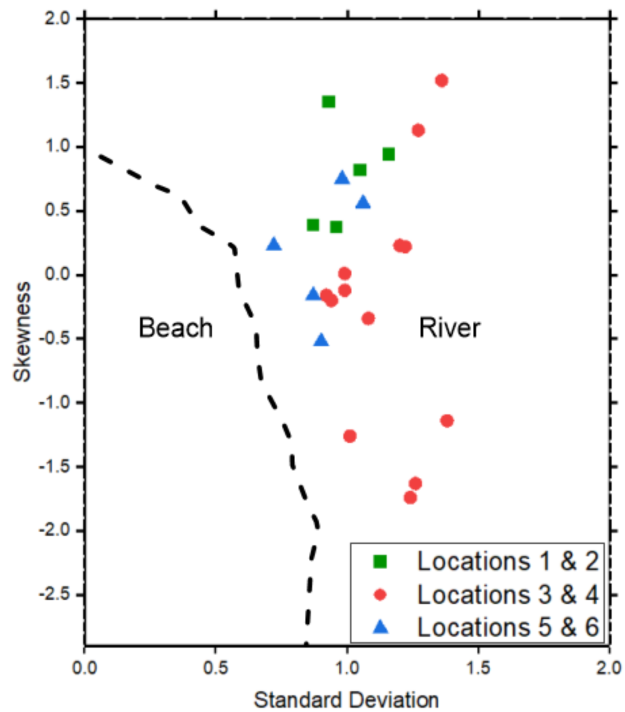

Figure 7: Binary plot of skewness versus inclusive graphic standard deviation, after [33]

analyzed samples were deposited in fluvial or mixed river-dune environment based on Friedman and Moiola and Weiser discriminating boundaries respectively since all the samples plotted in the river field. Similarly, the bivariate plot of standard deviation median size (Fig. 6) indicates similar result with all sample falling in the river field rather beach, employing [33] and [34] discriminatory boundaries. The same fluvial environment indicated by the plot of skewness versus median size which indicates that fluvial rather than wave processes played a key role in the deposition of the sediments based on [40] diagram (Fig. 6). The plot also shows that some of the samples fall outside river and beach fields.in the same diagram and thus fail to indicate neither of the two environments. In the same plot, all the samples fall in the river environment based on Friedman's [39] discriminatory scheme. Moreover, the samples were plotted on Friedman's [33] diagram which is a binary plot of standard deviation against skewness (Fig. 7). It easily can be seen from the plot that all analyzed samples fall in the river region thus indicating fluvial environment of deposition. By and large, the sediments of Amasiri Sandstone were deposited in fluvial environment based on the interpretation of binary plots of grain size statistical parameters.

Linear Discriminant Function (LDF) Analysis

Linear discriminant function (LDF) analysis was propounded by [24] to determine the fluctuations in energy and fluidity factor during deposition of the sediments [21, 24]. Sahu [24] proved that various LDFs, namely Y_1, Y_2, Y_3 and Y4 have predictable relationships with depositional processes and environments and therefore useful for discriminating between aeolian and beach (Y_1), beach and shallow marine (Y_2), shallow marine and fluvial or deltaic (Y_3) and, fluvial and turbidity current processes (Y_4). The LDFs Y_1, Y_2, Y_3, and Y_4 were computed based on the following mathematical relations:

To distinguish between aeolian processes and littoral processes, equation (5) was employed

$$Y_1 = -3.5688M_Z + 3.7016\sigma_I{}^2 - 2.0766\,SK_I + 3.1135K_G \quad (5)$$

The environment is "aeolian" if Y_1 is < −2.7411 and it is "beach" Y_1 if is > −2.7411 To distinguish between littoral processes (beach) and shallow marine, equation (6) was employed

$$Y_2 = 15.6534M_Z + 65.7091\sigma_I{}^2 + 18.1071SK_I + 18.5043K_G \quad (6)$$

The environment is 'beach' if Y_2 is < 65.3650 and it is shallow marine if Y2 is > 65.3650 Equation (7) was used to discriminate between shallow marine and fluvial depositional environments.

$$Y_3 = 0.2852M_Z - 8.7604\sigma_I{}^2 - 4.8932SK_I + 0.0482K_G \quad (7)$$

The environment is fluvial or deltaic if Y_3 is < −7.4190 and it is shallow marine of Y_3 is > −7.4190.

To distinguish between deposition by turbidity current and deposits resulting from fluvio-deltaic process, equation (8) was used.

$$Y_4 = 0.7215M_Z - 0.40304\sigma_I{}^2 + 6.7322SK_I + 5.2927K_G \quad (8)$$

If Y_4 is < 9.8433, it signifies deposition by turbidity currents whereas if if Y4 is > 9.8433 it is an indication of deposition by fluvial processes, where M_z, σ_I, Sk_I and K_G are the graphic mean, inclusive graphic standard deviation, Inclusive graphic skewness and graphic kurtosis of the studied samples respectively.

The result of the linear discriminant function analysis is presented in Table 2. The values of Y_1 which distinguish between aeolian and beach processes range from 3.0 tos 25.2 indicating that all analyzed samples were deposited in beach environment since all the values are greater than 2.7411 and thus infer that aeolian processes did not play any role in the accumulation of the sediments. The Y_2 values range from 116.0 to 166.0 and according to Sahu (1964), the separation between shallow agitated marine sands and those of beach or littoral is marked at 65. 3650 with lesser values indicating beach deposition. Thus the values of LDF Y_2 indicates that all the samples were deposited in shallow agitated marine waters rather than beach. Similarly. The values of Y3 which is used to discriminate between deposits resulting from fluvial or deltaic and shallow marine processes have values ranging from -20.8 to -0.8 with six samples (23 %) having values less than

Table 2: Result of LDF analysis and interpretations

Sample	Y_1	Inter.	Y_2	Inter.	Y_3	Inter.	Y_4	Inter.
L1-S3	8.2	Beach	155.9	Sh. mar.	-16.1	Fluvial	18.2	Fluvial
L1-S2	6.8	Beach	140.0	Sh. mar.	-14.4	Fluvial	15.8	Fluvial
L1-S1	4.2	Beach	129.9	Sh. mar.	-11.1	Fluvial	11.8	Fluvial
L2-S2	3.0	Beach	116.0	Sh. mar.	-10.4	Fluvial	10.1	Fluvial
L2-S1	5.3	Beach	133.2	Sh. mar.	-15.9	Fluvial	18.1	Fluvial
L3-S6	9.8	Beach	174.6	Sh. mar.	-18.2	Fluvial	21.6	Fluvial
L3-S5	15.2	Beach	166.3	Sh. mar.	-8.0	Fluvial	10.9	Fluvial
L3-S4	10.1	Beach	133.9	Sh. mar.	-3.5	Sh. mar.	1.5	Turbidity
L3-S3	11.5	Beach	147.2	Sh. mar.	-4.2	Sh. mar.	4.9	Turbidity
L3-S2	10.4	Beach	208.5	Sh. mar.	-20.8	Fluvial	28.5	Fluvial
L3-S1	5.6	Beach	115.1	Sh. mar.	-3.5	Sh. mar.	1.4	Turbidity
L4-S8	7.9	Beach	156.5	Sh. mar.	-13.0	Fluvial	13.7	Fluvial
L4-S7	6.8	Beach	148.9	Sh. mar.	-12.9	Fluvial	12.1	Fluvial
L4-S6	9.8	Beach	174.6	Sh. mar.	-18.2	Fluvial	21.6	Fluvial
L4-S5	5.9	Beach	122.8	Sh. mar.	-9.1	Fluvial	8.7	Turbidity
L4-S4	7.6	Beach	137.8	Sh. mar.	-8.8	Fluvial	9.9	Fluvial
L4-S3	5.5	Beach	125.3	Sh. mar.	-9.7	Fluvial	9.5	Turbidity
L4-S2	4.6	Beach	113.4	Sh. mar.	-8.2	Fluvial	7.2	Turbidity
L4-S1	4.7	Beach	115.4	Sh. mar.	-8.1	Fluvial	7.1	Turbidity
L5-S4	7.1	Beach	140.6	Sh. mar.	-13.2	Fluvial	14.7	Fluvial
L5-S3	6.5	Beach	97.3	Sh. mar.	-7.8	Fluvial	6.2	Turbidity
L5-S2	8.2	Beach	86.9	Sh. mar.	-6.5	Sh. mar.	3.2	Turbidity
L5-S1	3.8	Beach	85.5	Sh. mar.	-8.2	Fluvial	6.8	Turbidity
L6-S3	8.9	Beach	107.6	Sh. mar.	-5.2	Sh. mar.	2.9	Turbidity
L6-S2	7.9	Beach	125.0	Sh. mar.	-13.5	Fluvial	14.5	Fluvial
L6-S1	14.1	Beach	133.1	Sh. mar.	-0.8	Sh. mar.	0.9	Turbidity

Note: Inter. = Interpretation, Sh. mar. = Shallow marine.

-7.4910 and indicating deposition in fluvial or deltaic environment while majority of samples (77 %) originated in shallow marine environment. Also, the values of Y_4 range from 0.9 to 28.5 with 14 samples (54 %) having values greater than 9.8433 indicating fluvial environment of deposition while the rest 12 samples (46 %) indicate deposition by turbidity currents. Thus, the LDF analysis show that the sediments were deposited in environments ranging from fluvial through beach to shallow marine. Turbidity currents indicated for a few samples may be related those developed in fluvial setting as a result of rapid rate of deposition associated with flooding event in rivers rather than those occurring in deep marine settings (Sahu, 1964).

The binary plots of different combination of LDFs namely Y_2 versus Y_1, Y_3 versus Y_2 and Y_4 versus Y_3 (Fig. 8) were employed to further constrain the depositional environments of the Amasiri Sandstone. The binary plot of Y_2 aganst Y_1 indicates that all the samples fall in the beach /shallow agitated water. Moreover, the bivariate plot of Y_3 against Y_2 indicates that majority of the samples (69 %) fall in the agitated fluvial field while the remaining 31 % indicate agitated shallow marine environment (Fig. b). Furthermore, the binary plot of Y_4 versus Y_3 shows that majority of the samples (50 %) were deposited in fluvial environment, 25 % in fluvial environment with turbidity currents while the remaining 25 % deposited by turbidity current associated with shallow marine setting. Additionally, the bivariate plot of Y_4 against Y_3 shows a strong negative correlation the two LDFs. Thus, it is reasonable to deduce based on interpretation of LDF analysis that the depositional environments of Amasiri Sandstone range from fluvial through beach to shallow marine. The deduced depositional environments has some similarities with the conclusions of [3] and [7] who deduced tide-dominated, shallow subtidal and mixed storm and tide shallow marine to outer shelf depositional environments respectively. The agitated shallow marine or fluvial setting depicted by the LDF analysis is consistent with tidal, wave or storm processes deduced by the aforementioned authors.

Log Probability Plots and Depositional Processes

The shape, the number of populations, nature and truncation points of cumulative log probability plot reveal useful environmental parameters as they vary in a predictable and systematic manner that have significance with respect to the transportation, and deposition and therefore can furnish insight into current, waves, and depositional rate [16, 41]. The grainsize distribution characteristics as depicted by log probability plot suggests that multiple processes were responsible for their deposition, including fluvial, wave and tidal. The samples with 2 saltation populations suggests either beach or fluvial, processes were responsible for their deposition. According to [16], beach sediments are characterized by two saltation populations related to swash and backwash which produce laminae. Baiyegunhi et al [21] attributed two saltation populations to tidal environment of active opposing flood and ebb currents. River sediments differ from those of beach by possessing additional suspension load population. The absence of suspension population in most of studied samples either suggests winnowing of the clay by wave, tidal or current action in high energy beach to shallow marine setting (Visher, 1969). Samples with one saltation pop may suggests dune sand. Visher (1969) observed that beach sands are characterized by one saltation population.

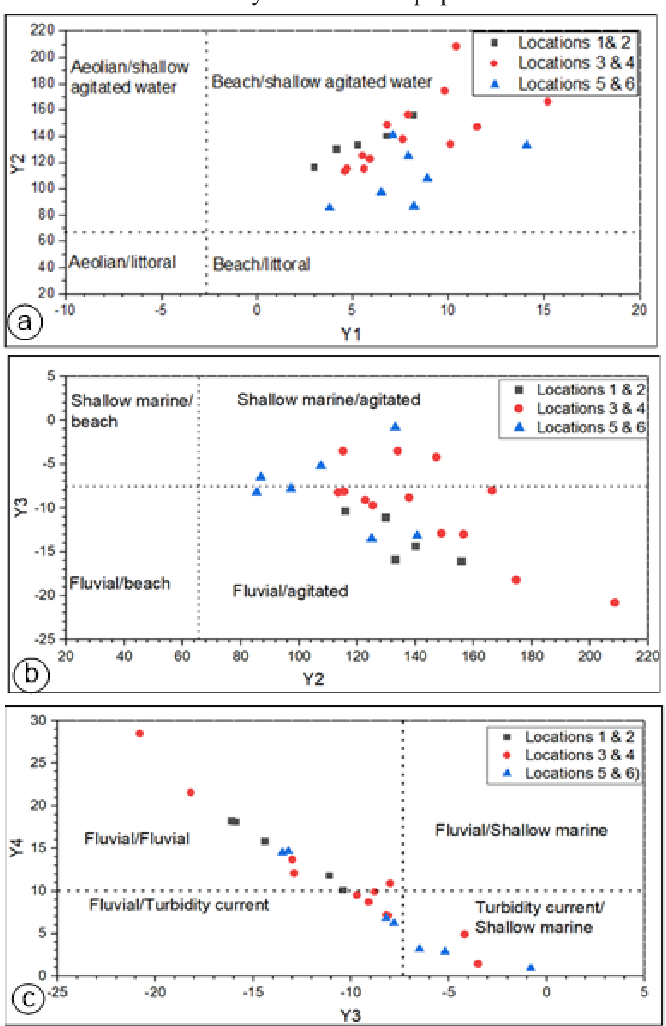

Figure 8: Binary plots of the various combinations of linear discriminant functions (a) Y_2 versus Y_1 (b) Y_3 versus Y_2 and (c) Y_4 versus Y_3.

or slow rate of deposition in high energy fluvial setting. This deduction is congruent with the low proportion of clay present in the sediments. The minor suspension fraction in some samples is characterized by very steep line segment, suggesting very good sorting.

CM Pattern

C-M pattern or Passega diagram was introduced by [42] to unveil the hydrodynamic forces that were prevalent prior to sediment deposition. According to the [42], the C-M pattern is geologic tool that can be used to reconstruct the condition of deposition of ancient and modern sediments. According to [43], C-M pattern plotted on logarithmic scale is characteristic of depositional agent and is useful for interpreting the hydrodynamic conditions during deposition and modes of transportation of clastic sedimentary particles. The C-M plot is a bivariate plot of coarser one- percentile value (C) in micron versus the median value (M) in micron on a logarithmic scale. The Passega diagram for the analyzed samples (Fig.) is partitioned into different fields related to different modes of transportation in fluvial , littoral and marine settings namely coarse grains transported by rolling (NO), rolling and bottom suspension (OP), suspension and rolling (PQ) , graded suspension (QR), and uniform suspension (finest sediments). The passage diagram indicates that major of the samples were transported by rolling and suspension since they fall within the region marked OP, about 12 % of the samples falling NO field were transported by rolling while roughly 15 % (four samples) in the PQ region indicates transportation by suspension and rolling. Therefore, the sediments of Amasiri Sandstone were transported as bedload and suspension load. the C-M pattern suggests that the current flow speed was relatively high since sand- sized grains were carried were carried partly in suspension. This is corroborated by the absence of uniform suspension which indicates slow flowing currents. Slow flowing rivers are characterized by uniform suspension load [44]

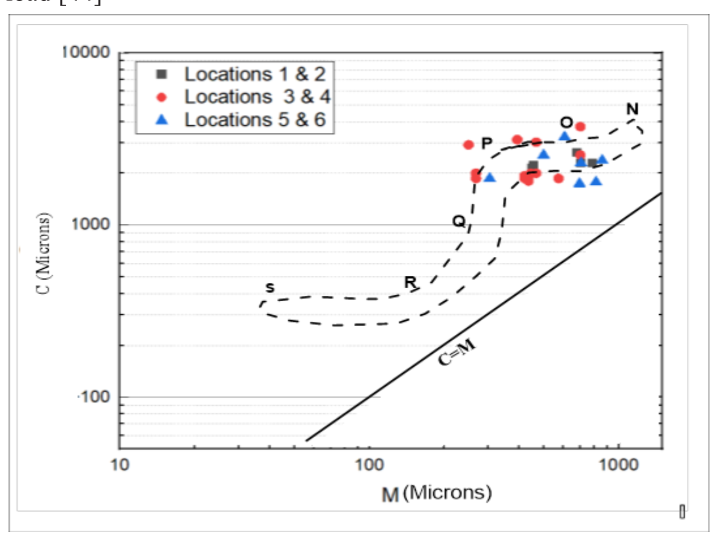

Figure 9: CM plot of samples of Amasiri Sandstone showing transport mechanisms, after [42].

Conclusion

The textural characteristics and depositional environment of 26 samples of Amasiri Sandstone have been investigated through grain size analysis. The sediments contain little proportion of clay fraction ranging from 0.00 to 6.14 % with an average of 0.89 % with most of the samples containing less than 1.00 % clay. The sediments are medium and coarse-grained with mean size ranging from 0.15 to 1.87φ and averaging 0.96 φ. They are moderately to poorly sorted with sorting values ranging from 0.72 to 1.38 φ and averaging 1.07 φ. The sandstone exhibit a wide range of distribution from strongly coarse skewed to strongly fine skewed with skewness values ranging from -2.31 to 1.52 φ and averaging -0.04 φ but indicate a narrow range of kurtosis from mesokurtic to leptokurtic distribution with values ranging from 0.99 to 3.49 φ and an average of 2.06 φ. They have bimodal with minor polymodal and unimodal distributions with a primary modal size of 1.2 φ. Bivariate plots of grain size parameters indicate fluvial environment of deposition. However, linear discriminant function analysis and log-probability plots indicate deposition in fluvial, beach, and shallow marine settings, and thus suggesting a possible deposition in high-energy transitional environment. The C-M pattern indicates that the sediments were transported mainly by rolling and suspension with subordinate fractions moved by rolling as well as suspension. Thus, Amasiri Sandstone was deposited in fluvial, beach, and agitated shallow marine environments.

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