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TEXTURAL ANALYSIS AND HYDRAULIC CHARACTERISTICS OF AJALI SANDSTONES OF OBOLLO-AFOR AND ENVIRONS IN ANAMBRA BASIN, SOUTHEASTERN, NIGERIA

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ABSTRACT

The movement and storage of groundwater are determined by the porosity and hydraulic conductivity of the medium, which defines its permeability. Hydraulic conductivity depends on both the properties of the porous material and the fluid, and it has long been linked to the grain-size distribution of granular media. This study highlights the textural characteristics and hydraulic conductivity of Ajali Sandstone in Obollo-Afor area (southeastern Nigeria). The investigation approach involved field sampling and collection of 12 sandstone samples from different outcrop locations followed by laboratory studies such as grain size analysis. Grain size analysis and textural studies show that the sandstones mean range from 0.96-1.87 (av. 1.52). Other parameters such as coefficient of uniformity (C_u) range from 2.133 to 4.263 (av. 0.399), while sorting values of 0.83-1.10 (av. 0.96) imply moderately sorted sediments. The sandstones are mostly platykurtic and coarse skewed indicating sand of fluvial origin ranging from channel floor, point bar to braided rivers. Analysis shows that the sediments were deposited in beach/shallow agitated and fluvial agitated environments. The Ajali Sandstone porosity values range from 36.53%-42.6% (av. 39.9) and the hydraulic conductivity values of 2.579-68.101m/day (av. 43.741m/day). These values of porosity and hydraulic conductivity are indications of high specific yield for the sandstone of the study area.

Keywords: Depositional Environment, Empirical Formulae, Grain Size Analysis, Hydraulic Conductivity

INTRODUCTION

The storage and transmission of groundwater is influenced by the hydraulic conductivity and porosity of the medium. Hydraulic conductivity (K) is a measure of the permeability of a porous medium. It is also defined as the rate at which a geologic material can transmit a liquid (water) under a hydraulic gradient (Alyamani and Sen, 1993; and Chakraborty et al., 2006). The hydraulic conductivity of water bearing rock depends on both properties of the porous medium and the fluid (for example density and viscosity).

It has been long known that hydraulic conductivity is related to the grain-size distribution of granular porous media (Freeze and Cherry, 1979). This inter-relationship is very useful for the estimation of conductivity values where direct permeability data are sparse such in the earliest stages of aquifer exploration. The knowledge of saturated hydraulic conductivity of a geologic material is considered essential for modeling the water flow in the formation, both in the saturated and unsaturated zone, and tracking transportation of water-soluble pollutants within geologic materials. The quest to seek out reliable techniques to determine the hydraulic conductivity of the aquifers become a notable dialogue as the relative spiral variation within the aquifer can be useful in formulating plans for the better groundwater development, management and conservation (Odong, 2007). Various techniques have been postulated to determine the hydraulic conductivity of saturated formations including field techniques: pumping tests of wells, auger hole tests, slug test and tracer test, of which are considered most trusted approach to estimate the hydraulic conductivity of saturated formations. Other technique includes laboratory methods and calculations from empirical formulae (Vukovic and Soro, 1992, Meinken and Stobar, 1997 and Todd and Mays, 2005). However, the accuracy of the estimation of hydraulic conductivity within field condition using field techniques is limited by lack of precise knowledge of aquifer geometry and hydraulic boundaries (Uma et al. 1989). Other limitations can be attributed to expensive cost of field operations and construction of associate testing wells, and long testing time. The Laboratory techniques are limited, due to problems of obtaining representative aquifer sample and often time consuming.

Alternatively, formulated empirical formulae based on grain size distribution characteristics have been adapted as alternative to laboratory techniques to estimate hydraulic conductivity. The empirical methods are cost effective and are not limited by hydraulic boundaries of the aquifer and its geometry but rather reflects almost all the transmitting properties of the porous media.

Numerous researchers have studied the interrelationship between the grain size of aquifer material and the hydraulic conductivity (Hazen, 1892; Slitcher, 1899; Terzaghi and Peck, 1964 and; Alyamani and Sen, 1993). The empirical formula has its own application limitations and provides only estimated hydraulic values for observed samples such as fluvial deposits consisting of fine to coarse sand and sandy gravels. Few formulas give reliable estimated values due to difficulty of including all possible variables in porous media. The conductivity values of the same aquifer materials estimated by different empirical formulae may yield differing values from each other in factor of 10 or even 20 (Vukovic and Soro, 1992, Odong 2007) and tend to tilt to the horizontal hydraulic conductivity of the porous media. For a better assessment of the empirical formulae, the estimated values can be compared with the horizontal hydraulic conductivity obtained from in situ methods.

The main focus of this work is the detailed geological mapping of Obollo Afor and its environs in Enugu, Anambra Basin Nigeria and the delineation of the paleoenvironment of deposition with emphasis on textural analysis, as well as extrapolation of the hydraulic conductivities of the area from the grain size analysis.

MATERIALS AND METHODS

Geographical Location

Obollo-Afor and its Environs is politically located in Udenu Local Government Area of Enugu State and geographically stretches from latitudes 6º52'0"N to 6º57'0"N and longitudes 7º29'0"E to 7º34'0"E. The present investigation covers an estimated area of about 86.49km^2. The climate of the area is hot and humid split into rainy season; March – October, which is characterized by heavy shower accompanied by thunderstorms and soil erosion- due to looseness of the soil, and dry season; November – February characterized by dry and dusty harmattan wind causing high evapo-transpiration rate. There is distinctive vegetation that exists within the study area; guinea savannah and tropical rainforest. The study area is bounded by several villages such as follows Ezima-Uno, Obollo-Afor, Ezima-Agu, Amolla, Igugu, Umundu Orba, Agbodu, Aba, Obollo-Etiti, Obollo-Eke, Imilike-Uno and Imilike-Agu.

Geology of Study Area

The study area is underlain by three geologic formations which are mainly, Mamu Formation, Ajali Formation and Nsukka Formation. Figure1 shows the geologic map of Obollo-Afor and environs. Mamu Formation (Lower Maastrichtian) consists of carbonaceous shale, grey shale and sandy shale (sandstone alternating with shale) and an upper fine sandstone subordinates. Ajali Formation (Maastrichtian-Danian) consists of medium to coarse grained, poorly consolidated and characteristic cross-stratified sandstones with subordinate shale and clays. Nsukka Formation which consists of an alternating succession of sandstones, dark shale, sandy shale, lateritic sand and ironstone is also evident in the area. All formations regionally dip 2°-5° to the SW direction. An interesting geomorphic characteristic of the study area is that the Nsukka Formation occurs mainly as outliers on the Ajali Sandstone (Figure 1). These outliers of Nsukka form ridge-like hills while the valleys are underlain by Ajali Formation (Umeji, 1980). The ridge and the valley are not reflective of deep-seated structures but are the resultant of weathering and differential of the erosion of clastic materials, which are remnants of Nsukka formation overlying the area. The trend of the ridge reflects the direction of eroding current.

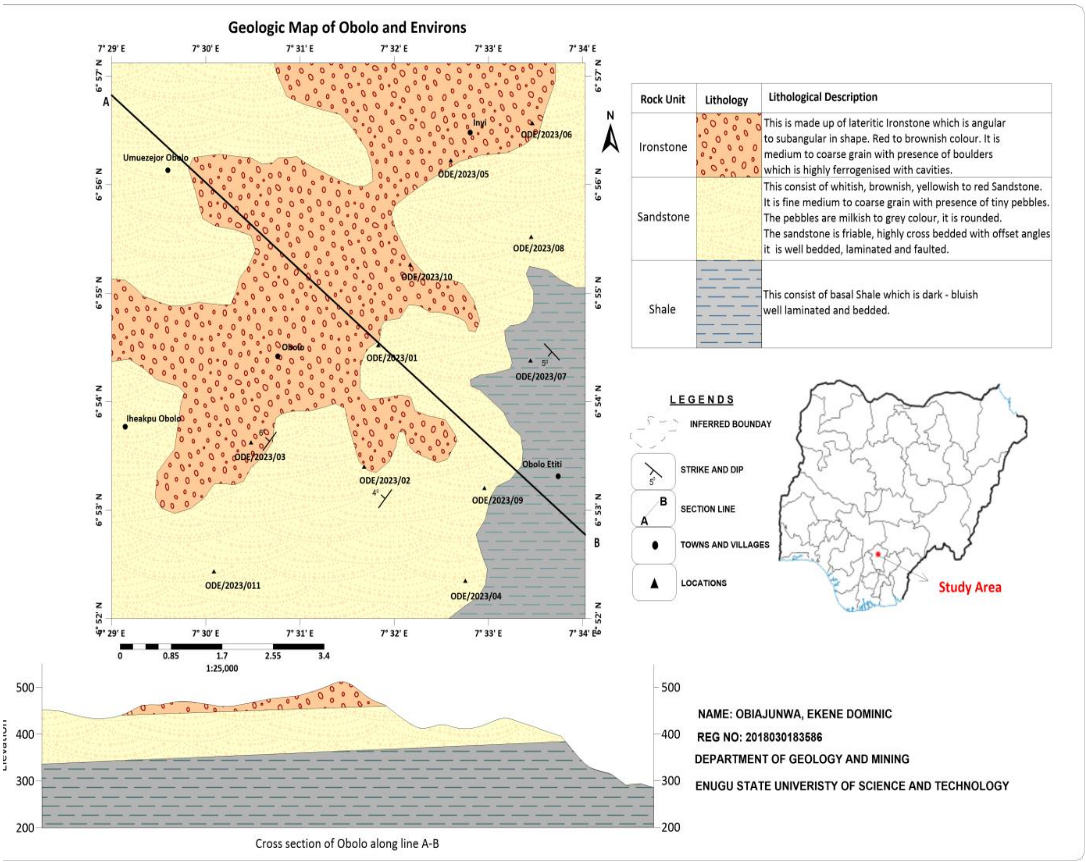

Figure 1: Geological Map of Obollo-Afor and Environs

Grain Size Analysis

Twelve sandstone samples were collected from various locations, samples were disaggregated in the laboratory with a rubber padded pestle as suggested by PettiJohn, (1975).100g of each disaggregated samples were measured using a weighing balance as test portions for sieve analysis. The test portions were sieved with a Rotag electrical automatic shaker for 15 minutes using a set of sieves with mesh size of 0.5 phi apart. Cumulative curves of the grain size distribution were plotted from the sieve result. The univariate, and bivariate parameters were computed based on Folk and Ward (1957), Sahu (1964) and (Blott & Pye, 2001). The Table 1 gives the standards by Folk and Ward (1957). The sieve technique was used to determine the grain size distributions. The effective grain size was characterized by the coefficient D_{10}, the value corresponding to 10% finer by weight. This was characterized by the sorting and the uniformity coefficient defined to be $C_u = D_{60}/D_{10}$ where D_{60} is the grain size corresponding to 60% finer by weight. If $C_u > 4$, the sample is commonly referred to as "poorly sorted", and if $C_u < 4$ the sample is "well sorted" (Fetter, 1994; 2001).

Table 1: Descriptive Measures of Grain Size Distribution (Folk and Ward, 1957) expressed in Phi units.

Mean Size	Sorting	Skewness	Kurtosis
$M_z = \frac{\Phi_{16}+\Phi_{50}+\Phi_{84}}{3}$	$\sigma_1 = \frac{\Phi_{84}-\Phi_{16}}{4} + \frac{\Phi_{95}-\Phi_5}{6.6}$	$Sk_1 = \frac{\Phi_{16}+\Phi_{84}-\Phi_{50}}{2(\Phi_{84}-\Phi_{16})} + \frac{\Phi_5+\Phi_{95}-2\Phi_{50}}{2(\Phi_{95}-\Phi_5)}$	$K_G = \frac{\Phi_{95}-\Phi_5}{2.44(\Phi_{75}-\Phi_{25})}$
Coarse sand	Very well sorted	Very finely skewed	Very platykurtic
0-1	<0.35	$^{+}0.3$ to $^{+}1.0$	<0.67
Medium sand	Well sorted	Finely skewed	Platykurtic
1-2	0.35 - 0.50	$^{+}0.1$ to $^{+}0.3$	0.67 – 0.90
Fine sand	Moderately well sorted	Symmetrical	Mesokurtic
2-3	0.50 - 0.70	$^{+}0.1$ to $^{-}0.3$	0.90 – 1.11
	Moderately sorted	Coarsely skewed	Leptokurtic
	0.70 - 1.00	$^{-}0.1$ to $^{-}0.3$	1.11 – 1.50
	Poorly sorted	Very coarsely skewed	Very Leptokurtic
	1.00 - 2.00	0.3 to $^{-}1.0$	1.50 – 3.00
	Very poorly sorted		Extremely leptokurtic
	2.00 – 4.00		<3.00
	Extremely poor sorted		
	>4.00		

Formulated Empirical Formulae for Hydraulic Conductivity Estimation

Empirical methods are used to define the hydraulic conductivity (K) of porous medium materials from the grain-size analysis, relating either K to some size property of sediments (Ayer et al., 1998). Vukovic and Soro (1992) summarized several empirical methods from previous experimental and research studies and presented a general formula:

$$K = \frac{g}{v} \cdot C \cdot f(n) \cdot d^2_e \quad (1)$$

Where K = hydraulic conductivity, g = acceleration due to gravity, v = kinematic viscosity, C = sorting coefficient, f (n) = porosity function and d_e = effective grain diameter. The kinematic viscosity (v) is relative to dynamic viscosity (μ) and the fluid (water) density (ρ) as presented as follows:

$$v = \frac{\mu}{\rho} \quad (2)$$

The values of C, f(n) and d_e is a function of the employed methods applied in the grain size analysis. According to Vukovic and Soro (1992), porosity (n) can be derived from the empirical model relationship with the coefficient of grain uniformity (U) as follows:

$$n = 0.255\,(1 + 0.83^U) \quad (3)$$

Where U is the coefficient of grain uniformity and is given by:

$$U = \frac{D_{60}}{D_{10}} \quad (4)$$

Where, D_{60} and D_{10} in the formulae represent the sieve grain diameter in (mm) retaining 40% and 90% of the sample.

The choice of the representative grain size is critical to the successful prediction of the hydraulic conductivity from the grain size distribution. In applying this equation, a fixed value of d_e is typically chosen to represent the entire range of grain sizes. Thus, the best representative value depends on the type of grain packing and the concentrations of the components by fractal weight. It is clear that successful prediction of hydraulic conductivity demands a representative value that will encompass the range of sizes in the grain size distribution. Furthermore, profound knowledge of the state of sorting and the packing is required.

A few adopted empirical formulae used for estimating the K values of aquifer materials are elaborated further as follows:

Hazen:

$$K = \frac{g}{v} * 6 * 10^{-4}[1 + 10(n - 0.26)\, d^2{}_{10}] \quad (5)$$

Hazen formula was initially derived to estimate the K of loose and uniformly graded but also useful for fine sand and gravel range, provided the sediments has a uniformity coefficient less than 5 and effective grain size between 0.1 and 3mm.

Slitcher: $K = \frac{g}{v} * 1 * 10^{-2}\, n^{3.287} D^2{}_{10}$ (6)

This formula is applicable for sand populations with effective grain diameter (D_{10}) between 0.01mm and 5mm

Breyer: $K = \frac{g}{v} * 6 * 10^{-4} \log\frac{500}{U}\, D^2{}_{10}$ (7)

The Breyer empirical formula does not take into account the porosity as a function in the equation to determine the K (porosity value is taken as 1). The formula is useful for analyzing heterogenous porous media with the poorly sorted grains with uniformity coefficient of 1 and 20 and effective gain size between 0.06mm and 0.6mm.

Kozeny-Carman:

$$K = \frac{g}{v} * 8.3 * 10^{-3}\left[\frac{n^3}{(1-n)^2}\right] D^2{}_{10} \quad (8)$$

It is initially proposed by Kozeny (1927) and late modified by Carman (1956), the equation is widely referred and used as Kozeny-Carman equation. It relates the K with the square of the effective grain diameter, porosity, and the physical properties of the fluid. This formula is not appropriate for either soil with effective diameter size (D_{10}) above 3mm or for clayey soils (Carrier, 2003).

Terzaghi: $K = \frac{g}{v} * C_T * \left[\frac{n-0.13}{\sqrt[3]{1-n}}\right]^2 D^2{}_{10}$ (9)

The Terzaghi empirical formula was formulated following equation using D_{10} as the effective grain diameter. Where C_T is the empirical coefficient dependent on the grain size and shape: $C_T = 10.7 * 10^{-3}$ for smooth grains and $6.1 * 10^{-3}$ for large grains. Terzaghi's formula is most applicable for large grain sand (Vukoic and Soro, 1992; Cheng and Cheng, 2007). An average value of $8.4 * 10^{-3}$ is used in this study.

USBR: $K = \frac{g}{v} * 4.8 * 10^{-4} D^{0.3}{}_{20} * D^2{}_{20}$ (10)

United State Bureau of Reclamation (USBR) formula estimates K from the effective grain size (D_{20}), and is independent of porosity. Hence, porosity function is a unit and the formula is most suitable for medium grain sand with uniformity coefficient less than 5 (Cheng and Cheng, 2007).

RESULTS AND DISCUSSION

The geologic implication of grain size parameters is evidently realized when parameters are plotted against each other which show their interrelationship in terms of scatter diagrams (Folk and Ward, 1957). Textural attributes of sediments like grain size distribution, mean, standard deviation, skewness, and kurtosis are widely used to reconstruct environment of deposition. These textural attributes were calculated from cumulative frequency graphs from sieve analysis results

(Figure 2). A summary of the textural attributes is presented in Table 2.

Grain Size Distribution Analysis

The grain size distribution curves indicate that about 88% (by weight) of the sediments are medium to coarse grained sand and fine gravels, while the remaining 12% are fine grained sand and coarse silt. Majority of the samples are medium grained suggesting deposition under moderate to high energy conditions. The samples were found to be uniformly graded across the study area, (Figure 2).

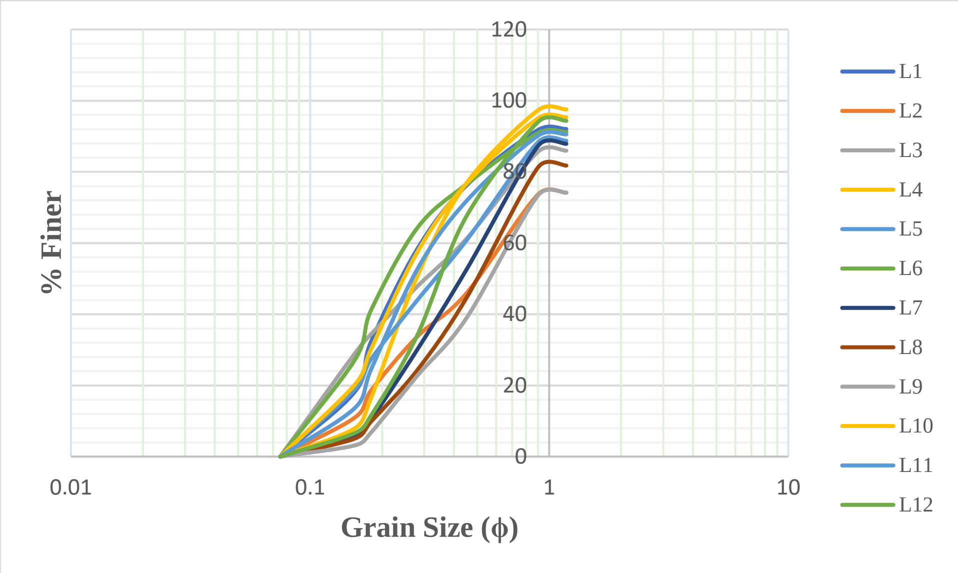

Figure 2: Grain size analysis graph for the study samples

Graphic Mean (Mz)

The mean phi size of the samples ranges from 0.96 to 1.87Φ with an average mean of 1.52Φ (Figure 3A). This range puts the sample sizes between coarse to fine sand (Boggs, 2014). This puts about 88% of the sample within medium-coarse sand range. This indicates that the majority of the sand sediments were transported through saltation process which was dependent on the hydrodynamic behavior with respect to their size, specific gravity and shape (Pettijohn *et al, 1987)*, and deposited in moderately high energy conditions while about 12% were deposited in relatively quiet energy conditions.

Inclusive Graphic Standard Deviation (σ_i)

The standard deviation is a measure of the sediment sorting. This reflects the kinetic energy of the deposition agent and its fluctuations. The standard deviation of the rock samples ranges from 0.93 to 1.10Φ with a mean of 0.96Φ (Figure 3B). According to the Folk and Ward (1957) classification, the sorting ranges from poorly sorted to moderately sorted. 25% of the sample is poorly sorted while 75% is moderately sorted. This indicates a moderate to relatively high fluctuation in the hydrodynamic energy of conditions of depositional environment (Friedman, 1961; Ayodele and Madukwe, 2019; Iheme et al, 2021). This indicates that the samples range from poorly sorted to moderately sorted within the study area.

Inclusive Graphic Skewness (Sk_i)

Inclusive graphic skewness is a measure of frequency distribution which indicates the position of the mean with respect to the median. Skewness results from combing of two different normal populations in different proportions and, may imply the dominance of coarse over fine and vice versa. It is geometrically independent of the sorting nature of the sample. For this analysis, skewness ranges from -0.49 to 0.36, with a mean of -0.07. According to Folk and Ward's (1957) classification, skewness ranges from strongly coarsely skewed to slightly strongly finely skewed. 75% of the sample is near symmetrical, coarse skewed, and fine skewed, 8.3% is slightly strongly fine skewed, and 16.7% is strongly coarsely skewed (Figure 3C). Skewness values also indicate the kinetic energy of the depositing medium. Negative values of skewness indicate coarsely skewed sediments and therefore indicates an agitated area with a higher than average deposition medium velocity. It also shows influence of cyclic current pattern of the depositing medium within a high energy prevailing environment, where wave surges disturb bottom sediments i.e. there are presence of extreme conditions like tidal variation, wave breaking and supply of detrital materials while positive skewness value is indicative of finely skewed sediments and low energy of the medium, (Sahu, 1964, Daune 1964)

Graphic Kurtosis (KG)

Graphic Kurtosis is a sensitive and valuable parameter for testing normality of a distribution (Sahu, 1964). For a normal distribution, the kurtosis value is 1.00. When it is less than 1.00, the curve is called platykurtic and it indicates better sorting in the tail portion of the sediments. When kurtosis value is more than 1.00, it is leptokurtic and indicates better sorting in the central portion of size curve. Kurtosis value thus reflects the fluctuation of energy conditions of the depositing medium (Folk and Ward, 1957). Kurtosis for this study ranges from 0.55 to 1.03 with a mean of 0.80 (Figure 3D). 58.3% of the sample is platykurtic, 16.7% is mesokurtic and 25% very platykurtic. This result indicates changes in the flow characteristics of the depositional medium (Baruah et al, 1997, Duane, 1964 and Rajganapathi et al, 2013). The kurtosis value shows the slight maturity of the sand particles which when compared with the sorting and mean, shows a better sorting at the tail than at the central point in a moderate to high energy (Duane, 1964).

Table 2: Statistical Analysis of Grain Size Parameters for Samples and Descriptions

Sample Number	Mean (M_z)	Standard Deviation (σ_i)	Skewedness (Sk_i)	Kurtosis (K_G)	Interpretation	Coeff. Value	Of Uniformity Remark
L1	1.85	0.96	-0.40	0.84	Medium sand, moderately sorted, strongly coarse skewed and platykurtic	2.513	Uniformly Graded
L2	1.20	1.08	0.24	0.55	Medium sand, poorly sorted, fine skewed, very platykurtic	4.620	Uniformly Graded
L3	1.45	1.10	0.17	0.76	Medium sand, poorly sorted, fine skewed and platykurtic	4.263	Uniformly Graded
L4	1.76	0.83	-0.22	1.03	Medium sand, moderately sorted, coarse skewed and mesokurtic	2.133	Uniformly Graded
L5	1.56	1.05	-0.07	0.65	Medium sand, poorly sorted, near symmetrical skewed and very platykurtic	3.803	Uniformly Graded
L6	1.92	0.98	-0.49	0.85	Medium grained, moderately sorted, strongly coarse skewed and platykurtic	2.519	Uniformly Graded
L7	1.29	0.91	0.07	0.76	Medium sand, moderately sorted, symmetrically skewed, platykurtic	2.519	Uniformly Graded
L8	1.14	0.90	0.20	0.83	Medium sand, moderately sorted, fine skewed, and platykurtic	3.533	Uniformly Graded
L9	0.96	0.93	0.36	0.66	Coarse sand, moderately sorted, strongly fine skewed, and very platykurtiic	3.620	Uniformly Graded
L10	1.87	0.94	-0.30	0.88	Medium sand, moderately sorted, coarse skewed, and platykurtic	2.664	Uniformly Graded
L11	1.72	0.95	-0.29	0.84	Medium sand, moderately sorted, fine skewed, platykurtic	2.609	Uniformly Graded
L12	1.49	0.85	-0.06	0.93	Medium sand, moderately sorted, coarse skewed, Mesokurtic	2.401	Uniformly Graded
Average	1.52	0.96	-0.07	0.80	Medium grained, moderately sorted, near symmetrically skewed and platykurtic		

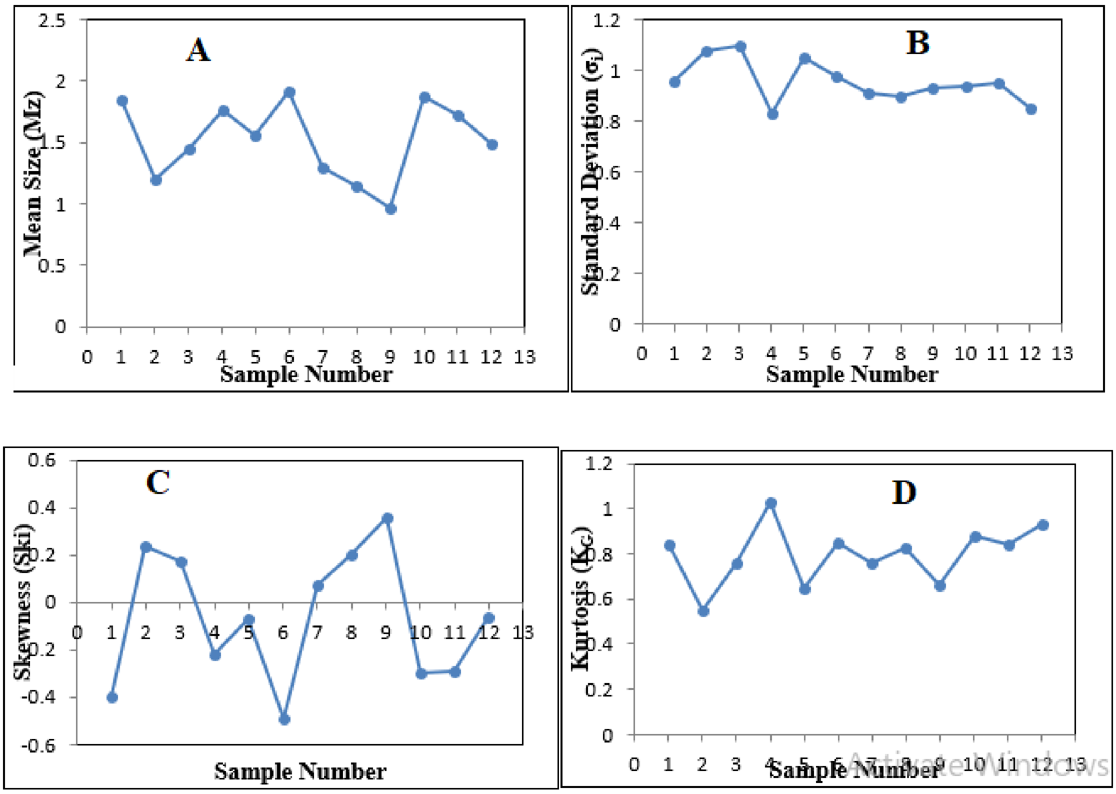

Figure 3: Horizontal variations of grain size parameters of the samples for mean size (A), standard deviation (B), skewness (C), and kurtosis (D)

Bivariate Plots of Statistical Parameters

The combination of several textural parameters in the form of bivariate plots has been used to identify depositional environment (Friedman, 1967). The bivariate plots are based on the assumption that statistical parameters reliably reflect differences in the fluid-flow mechanisms of sediment transportation and deposition (Sutherland, 1994). Several researchers have proven and documented that bivariate plots serve as reliable tools for identifying mechanisms of different environments of sedimentation. Furthermore, they reported that the bivariate plots are the most important and frequently used plots (Folks and Ward, 1957; Friedman, 1967, Moiola and Weiser, 1968 and Blott & Pye, 2001). These plots have also been attempted to differentiate between marine and fluvial sands. The bivariate plot of skewness against standard deviation, skewness versus mean, kurtosis against skewness, and standard deviation versus mean were used to distinguish between the different depositional settings.

Graphic Standard Deviation (Sorting) versus Mean Size

The bivariate plot of graphic standard deviation (sorting) against mean implies that the samples are poorly to moderately sorted, and are fine to coarse sand (Figure 4). Sediments that are moderately sorted out during longer transportation have relatively almost the same grain sizes and if there are different sizes the sediment were probably deposited close to its source or deposited quickly (Rajganapathi et al., 2013). Most of the sandstones are medium grained and moderately sorted due to lack of realistic time in the transporting medium and because of the grain to grain interaction, their sizes were reduced but to some extent. The presence of poorly sorted sandstones may point to a near source region. However, the presence of moderately sorted sediments indicates continuous reworking of the sediments by currents and waves (Moiola and Weiser, 1968).

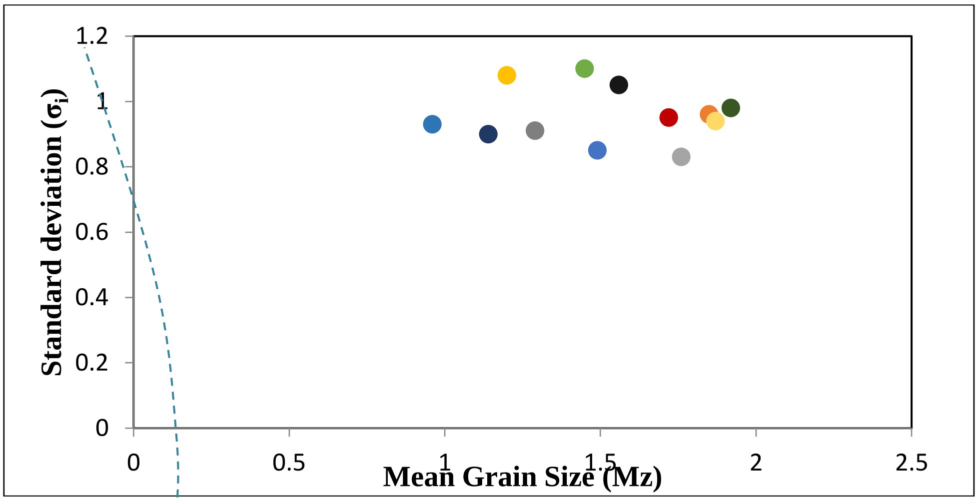

Figure 4: Depo-Environmental Discrimination of Bivariate plot of Mean size and Standard Deviation (Friedman, 1967)

Graphic Standard Deviation (Sorting) versus Skewness

The bivariate plot of graphic standard deviation (sorting) versus skewness shows that most of sand samples are mostly moderately sorted and coarse skewed to strongly coarse skewed (Figure 5). However, fine samples (L2, L3, L7, L8 and L9); L2 and L3 are fine skewed and poorly sorted, L7, L8 are fine skewed and moderately sorted while L9 is very fine skewed and moderately sorted. The poorly sorted to moderately sorted sediments are mainly clustered near the strongly coarse to coarse skewness.

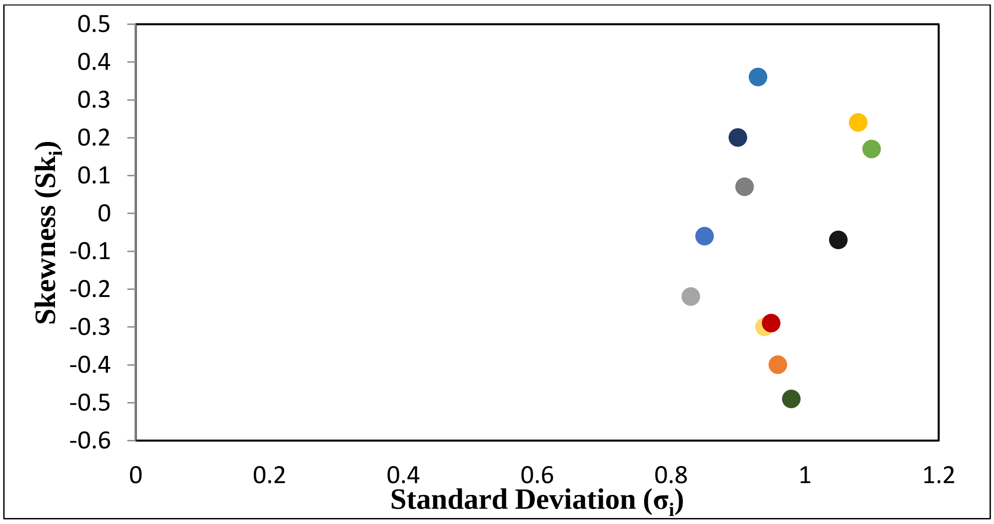

Figure 5: Depo-Environmental Discrimination of Bivariate plot of Skewness and Standard Deviation (Friedman, 1967)

Graphic Kurtosis versus Skewness

According to Friedman, (1967), the bivariate plot of kurtosis against skewness of a given sediment population is a powerful tool for distinguishing between depositional environments. The bivariate plot of graphic kurtosis versus skewness shows that the sand samples are Mesokurtic to very platykurtic (*i.e.* platykurtic in average) and are mostly coarse skewed (Figure 6). According to (Friedman, 1967), extreme high or low values of kurtosis imply that part of the sediment achieved their sorting elsewhere in a high energy environment.

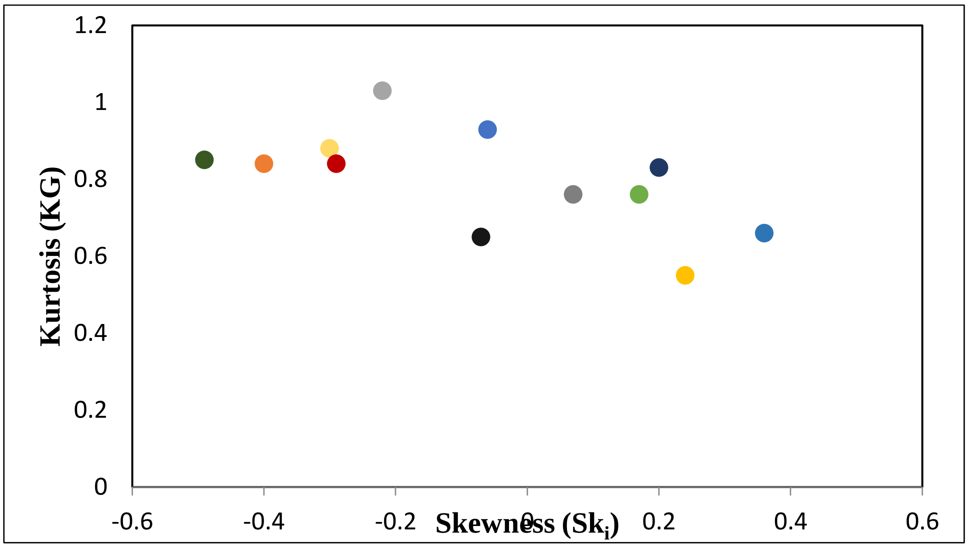

Figure 6: Bivariate plot of Kurtosis and Skeweness (Blott & Pye, 2001)

Linear Discriminate Function (LDF)

The use of statistical analysis to interpret the variations in energy and fluidity factors during/prior to sediment deposition seems to have a very good correlation with the different processes and depositional environments (Sahu, 1964). The (Sahu, 1964) linear discriminant functions of Y_1 (aoelian and beach), Y_2 (beach and shallow marine), Y_3 (shallow marine and Fluvial) and Y_4 (fluvial and turbidity current) were modified and used to discriminate between the different processes and depositional environments.

Furthermore, in order to distinguish environment of deposition between Aeolian and beach, the following equation has been applied:

Y_1 (Aeolian: Beach) = -3.5688Mz + 3.7016σi^2 - 2.0766Sk_i + 3.1135KG (11)

Where if Y_1 is $\geq$ -2.7411, the environment of deposition is beach, and if Y_1 is $\leq$ -2.7411, the environment of deposition is Aeolian.

To delineate the environment of deposition between beach and shallow marine, the following equation has been applied:

Y_2 (Beach: Shallow marine) = 15.6534Mz + 65.7091σi^2 + 18.1071Ski + 18.5043KG (12)

Where if Y_2 is $\geq$ 63.3650, the environment of deposition is shallow marine, and if Y_2 is $\leq$63.3650, the environment of deposition is beach.

To distinguish environment of deposition between shallow marine and fluvial, the following equation has been applied:

Y_3 (Shallow marine: Fluvial) = 0.2852Mz - 8.7604σi^2 - 4.8932Ski + 0.0428KG (13)

Where if Y_3 is $\geq$ -7.4190, the environment of deposition is shallow marine, and if Y_3 is $\leq$ -7.4190, the environment of deposition is fluvial.

To distinguish environment of deposition between fluvial and turbidity current, the following equation has been applied:

Y_4 (Fluvial: Turbidity current) = 0.7215Mz - 0.4030σi^2 + 6.7322Ski + 5.2927KG (14)

Where if Y_4 is $\leq$ 9.8433, the environment of deposition is turbidity deposition, and if Y_4 is $\geq$ 9.8433, the environment of deposition is fluvial.

(M_z = mean, σ_i = standard deviation, Sk_i = skewness and K_G = kurtosis).

Obollo-Afor sand sample values for Y_1, Y_2, Y_3 and Y_4 range from -0.07 to 1.32, 86.92 to 119.35, −11.03 to −4.41 and 2.2 to 6.26, respectively (Table 3).

Y_1 values did not show much discrimination among the samples as it interprets all the samples as beach deposits, while Y_2 values show that 8 samples (100%) fall in the shallow marine agitated environments category. In addition, 5 samples (41.7%) of the samples indicate a fluvial -deltaic depositional environment according to Y_3 discrimination and 7 samples (58.3%) are of shallow marine agitated depositional environment.

According to Y_4, all samples (100%) fall in the fluvial turbidity current depositional environment. Scatter plot of Y1 and Y2 shows that the samples fall in Beach/shallow agitated environment (Figure. 7a). The scatter plot of Y2 and Y3, indicate that about 58.3% of the samples are deposited in Shallow marine agitated, while the other 41.7% are fluvial agitated (Figure 7b). The plot of Y_4 and Y_3 (Figure 7c) shows that 41.67% of the samples are turbidity current deposits of fluvial origin, while 58.3% of the samples are turbidity current deposits associated with shallow marine agitated environment.

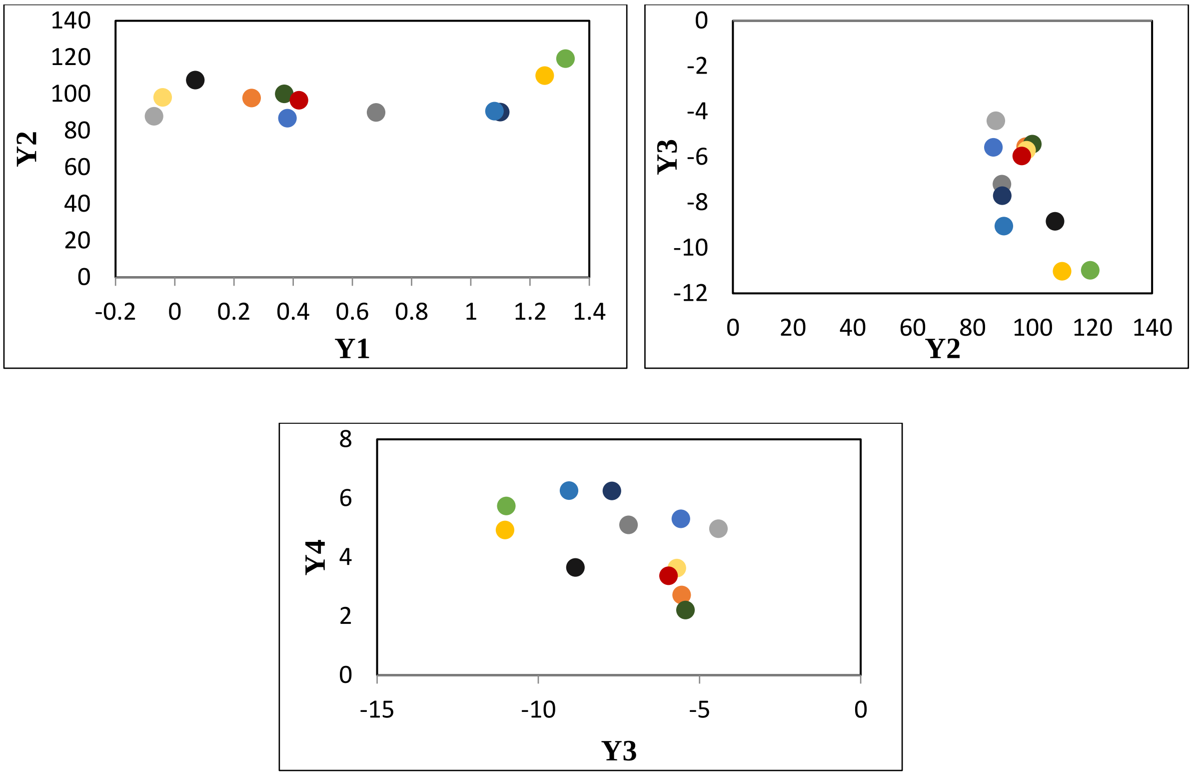

Figure 7: Linear Discriminate Function (LDF) sector plots for (a) Y1 vs Y2 (b) Y2 vs Y3 and (c) Y3 vs Y4 for the sediments at Obollo-Afor and its environs

Hydraulic Characteristics of the Sediments

Determination of Hydraulic Conductivity-values from Grain-Size Analysis

From the grain-size distribution curves in Figure 2, the samples were classified, diameters of soil particles retained at 90%, 80%, 70% and 40% by weight determined, and the coefficients of uniformity, intercepts and porosity values were calculated.

All these results, from which hydraulic conductivities were calculated using the empirical formulae, are presented in Table 4. Since the kinematic coefficient of viscosity is also necessary for the estimation of hydraulic conductivity, a value of 0.0874 m^2/day derived for a water temperature of 20ºC is used in this study.

The overall results showed the calculated hydraulic conductivities by different empirical formulae varied relatively. The USBR formulae gave values from 2.58 m/day to 18.75 m/day with mean of 9.14 m/day. Slitcher and Breyer reveal values 3.35 m/day to 54.73 m/day with mean 9.70 m/day and 25.92 m/day respectively. Terzaghi gave values from 5.78 m/day to 38.42 m/day with mean 16.93 m/day. Kozeny-Carman and Hazen methods gave values from 9.29 m/day to 68.10 m/day with mean values of 29.37 m/day and 28.0 m/day respectively.

The estimated results indicated that, the hydraulic conductivities calculated using the USBR and Slitcher methods are in all cases lower than for other methods which is consistent with the findings of Vukovic and Soro (1992) and Cheng and Chen (2007). These methods are always considered inaccurate (Odong, 2007). Terzaghi method also gave the slightly lower values which may be attributed to the use of an average value ($8.4x10^{-3}$) of sorting coefficient and also the formula is feasible in large grain size samples. Average conductivity values by Hazen, Kozeny-Carman and Breyer gave similar values with can be considered accurate but within stipulated conditions to which each formula exhibit more accurate estimated values. Breyer method is most useful for analyzing heterogeneous sample with well-graded grains (Pinder and Celia 2006). However, for less heterogeneous (poorly graded) the method underestimated the hydraulic conductivities values. Hazen formula which is based only on the d_{10} particle size is less accurate than the Kozeny-Carman formula which is based on the entire particle size distribution and particle shape (Carrier 2003). Based on the conditions stated under each method, the different statistical grain size methods are suitable for the determination of hydraulic conductivity of aquifer materials in the study area. For this particular work the Breyer, Kozeny-Carman and Hazen formulae will be considered the most suitable, Terazhi will be considered not idea because of it typical functionality within large grain size samples. The USBR though is applicable is consider lacking because of conditions- not considering porosity of the media though within range of medium grain size.

Table 3: Linear Discriminate Function (LDF) values and Depositional Environments (Sahu, 1964)

Sample No.	Mean (M_z)	SD (σ_i)	Skewness (Sk_i)	Kurtosis (K_G)	Discriminate Function				Environment of Deposition			
					Y1	Y2	Y3	Y4	Y1	Y2	Y3	Y4
L1	1.85	0.96	-0.4	0.84	13.46	97.82	-5.55	2.72	Beach	Shallow Marine	Shallow Marine	Turbidity
L2	1.2	1.08	0.24	0.55	9.81	109.95	-11.03	4.92	Beach	Shallow Marine	Fluvial	Turbidity
L3	1.45	1.1	0.17	0.76	11.67	119.35	-10.99	5.73	Beach	Shallow Marine	Fluvial	Turbidity
L4	1.76	0.83	-0.22	1.03	12.50	87.89	-4.41	4.96	Beach	Shallow Marine	Shallow Marine	Turbidity
L5	1.56	1.05	-0.07	0.65	11.82	107.62	-8.84	3.65	Beach	Shallow Marine	Fluvial	Turbidity
L6	1.92	0.98	-0.49	0.85	14.07	100.02	-5.43	2.2	Beach	Shallow Marine	Shallow Marine	Turbidity
L7	1.29	0.91	0.07	0.76	9.89	89.94	-7.2	5.09	Beach	Shallow Marine	Shallow Marine	Turbidity
L8	1.14	0.9	0.2	0.83	9.24	90.05	-7.71	6.24	Beach	Shallow Marine	Fluvial	Turbidity
L9	0.96	0.93	0.36	0.66	7.93	90.59	-9.04	6.26	Beach	Shallow Marine	Fluvial	Turbidity
L10	1.87	0.94	-0.3	0.88	13.31	98.18	-5.7	3.63	Beach	Shallow Marine	Shallow Marine	Turbidity
L11	1.72	0.95	-0.29	0.84	12.70	96.52	-5.96	3.37	Beach	Shallow Marine	Shallow Marine	Turbidity
L12	1.49	0.85	-0.06	0.93	11.01	86.92	-5.57	5.3	Beach	Shallow Marine	Shallow Marine	Turbidity

Table 4: Grain size distribution and hydraulic conductivity values computed from the empirical formulae

S/N	d_{10} (mm)	d_{20} (mm)	d_{30} (mm)	d_{60} (mm)	C_u	N	C_c	Hazen (m/day)	Kozeny-Carman (m/day)	Breyer (m/day)	Slitcher (m/day)	Terzaghi (m/day)	USBR (m/day)
L1	0.118	0.157	0.176	0.297	2.513	0.415	0.879	17.964	20.353	16.194	6.533	11.453	5.725
L2	0.147	0.189	0.256	0.679	4.620	0.363	0.656	22.194	17.828	22.241	6.529	11.224	8.771
L3	0.102	0.111	0.159	0.436	4.263	0.370	0.565	11.054	9.293	10.892	3.347	5.776	2.579
L4	0.160	0.190	0.220	0.342	2.133	0.426	0.882	34.053	42.041	30.697	13.090	23.003	8.878
L5	0.117	0.157	0.196	0.443	3.803	0.381	0.743	15.306	13.829	14.675	4.849	8.411	5.725
L6	0.104	0.141	0.159	0.262	2.519	0.414	0.930	13.900	15.642	12.574	5.035	8.824	4.471
L7	0.217	0.229	0.281	0.547	2.519	0.414	0.661	60.514	68.101	54.743	21.919	38.417	13.640
L8	0.181	0.251	0.329	0.639	3.533	0.387	0.933	37.626	35.367	35.651	12.218	21.240	16.844
L9	0.200	0.263	0.357	0.725	3.620	0.385	0.880	45.535	42.240	43.314	14.665	25.476	18.754
L10	0.114	0.153	0.179	0.304	2.664	0.410	0.930	16.438	18.009	14.948	5.859	10.259	5.395
L11	0.133	0.169	0.200	0.346	2.609	0.412	0.867	22.553	25.042	20.428	8.104	14.197	6.782
L12	0.172	0.218	0.262	0.412	2.401	0.418	0.973	38.617	44.645	34.704	14.213	24.934	12.180
Minimum	0.102	0.111	0.159	0.263	2.133	0.363	0.565	11.054	9.293	10.892	3.347	5.776	2.579
Maximum	0.217	0.263	0.357	0.725	4.263	0.426	0.973	60.514	68.101	54.743	21.919	38.417	18.754
Average	0.147	0.186	0.231	0.453	3.099	0.399	0.8245	27.9795	29.36583	25.922	9.697	16.934	9.145
Standard Deviation	0.039	0.047	0.066	0.159	0.825	0.021	0.134	15.230	17.297	13.873	5.520	9.683	5.128

The values from grain size analysis parameter tests and those from the empirical estimations for the Ajali Formation fall within a range of 10^{-4} to 10^{3} m/day for clean sands; interpreted to be permeable to highly permeable (Freeze and Cherry, 1979).

The grain size distribution analysis of sandstone shows that the sampled outcrops is attributed with ranges from fine to coarse quartz arenite-poorly to moderately sorted, which indicate a high degree of sorting for the sandstone aquifer. The aquifer of this sandstone with high permeability and porosity depicted from the aforementioned values has specific yields which are reasonable for economic water supply (Obasi et al, 2013).

CONCLUSION

The grain size distribution curves indicate that about 88% (by weight) of the sediments are medium to coarse grained sand and fine gravels, while the remaining 12% are fine grained sand and coarse silt. The sorting indicates that the sample range from moderately sorted to poorly sorted. Majority of the sediments in the study area are medium to coarse grained indicating the short distance of travel. The skewness is strongly fine skewed to strongly coarse skewed, also indicates a transition between a quiet to moderate area and an agitated area with a higher than average deposition medium velocity. The kurtosis is very platykurtic to mesokurtic indicating better sorting at the tail than at the central point in a moderate to high energy. The environment of deposition of the study area using LDF shown to be beach/shallow agitated and fluvial agitated environments. Based on the conditions stated under each method, the different statistical grain size methods are suitable for the determination of hydraulic conductivity of aquifer materials in the study area. Average conductivity values by Hazen, Kozeny-Carman and Breyer gave similar values with can be considered accurate but within stipulated conditions to which each formulae exhibit more accurate estimated values. The Breyer, Kozeny-Carman and Hazen formulae will be considered the most suitable for this study, Terazhi will be considered not idea because of it typical functionality within large grain size samples only. The USBR though is applicable is considered lacking because of condition devoid of porosity of the media though within range of medium grain size, resulting to values underestimation. The estimated hydraulic parameters (C_u = 2.155 – 4.263, n = 36.3% to 42.6% and K = 2.579– 68.101 m/day) in addition to statistical parameters (such as skewness, kurtosis, graphic mean and standard deviation) are indications of high aquiferous potentials of the sandstone in terms of groundwater occurrence for economic supply.

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