INTEGRATED SEDIMENTOLOGICAL AND PETROPHYSICAL CHARACTERISTICS OF THE EOCENE NANKA FORMATION AT OGBUNIKE AREA, SOUTHEAST, NIGERIA.

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ABSTRACT

The Eocene Nanka Formation at Ogbunike type localtiy was studied to ascertain the lithostratigraphy, petrophysical properties and depositional environment. Petrophysical properties of reservoir rocks are influenced by current velocity, degree of current variance and grain size parameters. These properties are partly controlled by facies characteristics which in turn are related to depositional environment. Field mapping utilizing bearing and pacing, and spot sampling based on lithologic variation was adopted along six lithogic profiles. Measurement of azimuths and dips of cross beds were taken for paleocurrent analysis. A total of 18 representative samples were collected for granulometric, thin section and heavy mineral petrographic analyses. Detailed sedimentology field study and lithologic description revealed the section to be 14.78m thick (vertical thickness) with a lateral extent of about 82m consisting of ironstone/sandstone, pyritic grayish shales, interstratified claystone/mudstone and heterolite. Azimuths of NE-SW and NW-SE directions described the paleocurrents of the formation with dominant polar-unimodal orientation, high vector strength (mean of 14.18o) and low variance ranging from 248.5 to 368.9. The sediments are bimodal to polymodal suggesting different parent sources, predominantly positively skewed, leptokurtic and dominantly moderately sorted suggesting fair porosity, fair permeability, heterogeneous reservoir unit, moderate energy of transportation medium and fluvial environment. Heavy minerals found indicated mixed provenance and mineralogical maturity. The study revealed that the sediments are ferrugineous, texturally sub-mature to mature, mineralogically super mature, fine to medium grained, moderately sorted and deposited in a near-shore fluvial environment under a moderate energy condition. The sediments are characterized by fair permeability and effective porosity, heterogeneous to slightly homogeneous reservoir unit.

Keywords: *Grain size, Depositional Environment, Provenance, Porosity, Permeability, Reservoir.*

INTRODUCTION

The Anaambra Basin was formed following the Santonian tectonic pulse on a sub-basin formed by the differential subsidence of the fault block in the southern Benue Trough. It was a deltaic complex filled with a lithostratigraphic unit akin to those of the Cenozoic Niger Delta (Nwajideand Reijers, 1996).Petrophysical properties of reservoir rocks which include porosity, permeability, etc., are influenced by current velocity, degree of current variance, grain size, sorting, etc. These properties are partly controlled by facies characteristics which in turn are related to depositional environment. Outcrop models both increase the knowledge of reservoir heterogeneity and provide the foundation for which the rest of the subsurface reservoir and simulation models can be built (Reynolds *et al*., 1998; Schatzinger and Tomutsa, 1999; Grammer*et al.*, 2004). Effort in this direction has lent credence to an integrated evaluation of the sedimentological and petrophysical characteristics of the Ogbunike sandstone (Eocene Nanka Formation).

Location and Accessibility

The study area lies within Longitude $6^0 51^1 55^{11}$E and Latitude $6^0 10^1 48^{11}$N and falls within Ameki Formation of the Anambra Basin (fig.1). The exposure is about 14.78m thick (vertical thickness) and a lateral extent of about 82m.

The outcrop is accessible by good road network, located in Ogbunike area on the left flank of the Onitsha bound Onitsha – Enugu express way, near toll gate, Anambra State, Southeast, Nigeria.

Figure 1. Geological map of Anambra State showing location of study area with photograph inserted (Modified after Nigerian Geological Survey Agency, 2006).

GEOLOGIC BACKGROUND

The Anambra Basin is a Cretaceous/Tertiary basin, which is the structural link between the Lower Benue Trough and the Tertiary Niger Delta Basin. Anambra Basin consist of the Mamu Formation, Ajali sandstone, Nsukka Formation, Imo Formation, Ameki Group and Ogwashi-Asaba (Nwajide, 2013). The Ameki Group consists of the Nanka Sand, Nsugbe Formation, and Ameki Formation (Nwajide, 1979), which are laterally equivalent. The age of the formation has been considered to be either early Eocene (Reyment, 1965) or early middle Eocene (Adegoke, 1969). The depositional environment has been interpreted as estuarine, lagoonal, and open marine, based on the faunal content. White (1926) interpreted an estuarine environment because of the presence of fish species of known estuarine affinity. Adegoke (1969), however, indicated that the fish were probably washed into the Ameki Sea from inland waters, and preferred an open marine depositional environment. Nwajide (1979) suggested environments that ranged from nearshore (barrier ridge-lagoonal complex) to intertidal and subtidal zones of the shelf environments, whereas Fayose and Ola (1990) suggested that the sediments were deposited in marine waters between the depths of 10 m and 100 m.

Acra *et al* ., (2013) and Oboh *et al.,* (2005) opined that the univariate, bivariate, multivariate, pebble morphometry and sedimentary structures of the Paleocene – Eocene sediments in the Anambra Basin indicate that the sandstones were deposited in a variety of depositional settings such as fluvial, lagoonal, tidal and shallow marine environments and the sediments are derived from two sources namely the basement area and the preexisting sedimentary terrain which exist east and northeast. The stratigraphic architecture shows various facies associations such as the tidally influenced channels, braided fluvial channels, flood plains and fluvial channels. The sands are medium-coarse grained mainly moderately sorted, subrounded, negatively to positively skewed and leptokurtic in distribution. They suggested a four facies model – fluvial channels, braided fluvial channels, tidally influenced channels and flood plain deposits all being deposited at varying environments based on high, moderate or low energy fluctuation and the dominant system either fluvial or tidal incursions, a coarsening upwards sequence, flaser and lenticular bedding, herringbone structures, tidal bundles, clay draped reactivation surfaces, bimodal -bipolar paleocurrent distribution and the trace fossil Ophiomorpha and Skolithos.

LOCAL GEOLOGIC SETTING

From detailed sedimentologic field mapping exercise, the studied section (figure 2) is about 14.78m thick and made up of ironstone/sandstone, shale, sandstone/siltstone, interstratified calcareous clay/mudstone and heterolithicsandstone lithologies from the base. The shales are dark – grey in colour, fissile, and clayey in some places. The sandstone intervals are parallel to wavy laminated, fine to medium grained, yellowish to pinkish brown and dark colour, occasionally highly compacted/cemented and friable. The heterolithic sandstone is medium to coarse grained, white to pinkish brown with degree of ferruginization and parallel to wavy lamination. The main characteristic sedimentary structures are flaser bedding, planar/troughs cross beddings with intervening mud drapes. There is also presence of reactivation surface and iron stains at various intervals. The fossil assemblage's present include skolithus, ophiomorpha, with bioturbations at various intervals. A total of six (6) lithologic profiles were logged.

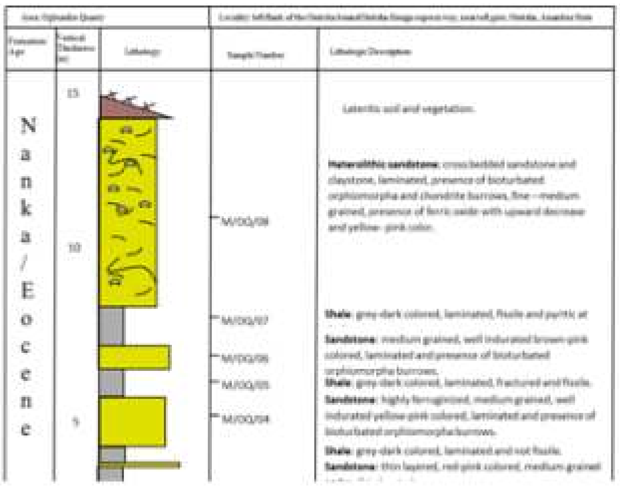

Figure 2. Lithologic log of the studied section

MATERIALS AND METHODS

Field Appproach

The exercise was limited to surface geological studies utilizing bearing and pacing method. The field study entailed carrying out detailed geological mapping of the rock types in the study area. Field observations including grain texture, colour and mineralogical composition, measurements of dips and azimuth of cross-beddings, in-situ measurements of length and breadth of ichnofossils, thickness and lateral extent of beds, taking photographs of important sedimentary structures and logging of exposed vertical sections were done. Measurements of dips and strikes (azimuths) of the cross-beds were taken from the foreset planes for palaeocurrent analysis. Spot sampling method was adopted along lithologic profiles for sample collection. The outcrop was trenched at each sample collection point in order to obtain fresh samples. Samples collected were labeled with reference to locality from the base to the top. Separate sample bags were used for each sample to avoid contamination.

Laboratory Approach

The laboratory works carried out include heavy mineral separation, granulometric, heavy mineral separation and paleocurrent analyses. A total of eighteen fresh samples were collected from Ogbunike quarry for laboratory analyses.

Paleocurrent Analysis

Paleocurrent data measured from the foreset planes of cross-bedded sand facies in the field were synthesized for calculation of the mean vector azimuths (MVA), variance and vector strength using Steinmetz (1962) method.

Granulometric Analysis

The grain size distributions of nine representative samples were mechanically determined in Sedimentology Laboratory/Grain Size of the Geology Department, University of Ibadan, Ibadan, Nigeria. Pulverized and quartered fraction was sieved using Durham Geo-Slope shaker for 20 minutes agitation of 100g sample component. Standard sieve set in the order of mesh sizes 1/2? were used. The fraction of each mesh size was weighed for statistical analysis based on the procedure of Folks and Ward (1957).

The results of the statistical data obtained from sizes distribution was used to deduce the mode of transportation and depositional environment of the sandstone. Sieve data plotted on semi-log sheet were used to determine the 50th percentile or median diameter (? 50), mean, sorting, skewness and kurtosis. These parameters were then substituted into the empirical formula proposed by Krumbrien and Monk (1942) to estimate permeability of the reservoir intervals.

Heavy Mineral Separation

Eight samples were subjected to heavy minerals petrographic analysis in the Geochemistry and Petrographic Laboratories of the Department of Geology, University of Ibadan. Each sample was treated with dilute hydrochloric acid (HCl) and acetone (CH3COOH) to remove carbonate clay or iron oxide coating and clean the grains which was accompanied by drying in an oven. 5g of each treated sample was taken and put in a separate funnel containing bromoform. Gravity settling technique was adopted for the separation of the heavy minerals. The separated heavy minerals were mounted on glass slide for each sample using Canada balsam.
Examination and identification of the heavy minerals was carried out using a petrographic microscope on the basis of their optical properties. The number, size and shape of the different opaque and non-opaque minerals were noted and their percentages also estimated. The maturity index or ZTR index was calculated using Hubert (1962).

RESULTS AND DISCUSSION

PALEOCURRENT ANALYSIS

The paleocurrent distribution of the outcropping units shows a dominant polar-unimodal orientation or pattern with vector strength (mean of 14.18o) of high dispersion. The primary mode is in the Northeast direction approximately and the secondary mode in the southwest direction. These unimodalpaleocurrent patterns indicate a fluvial environment. The rose diagrams (Figure 3) also suggest Northwest and Southwest provenance for the sediments. Azimuths of NE-SW and NW-SE directions described the paleocurrents of the formation. Table 1 shows the summary of the paleocurrent parameters of the Ogbunike sandstone. Table 2 also shows paleocurrent results and their environmental implications.
The variance ranges from 248.5 to 368.9 indicating a fluvial environment. The low variance also suggests high vector strength, lower permeability and effective porosities, poor reservoir sediment sorting and higher reservoir heterogeneity (Figure 4).

Azimuth A	Dip D	Sine A	Cos A	Cos D	(A1-A)	$(A1-A)^2$
75	9	0.97	0.26	0.99	-3.61	13.042
103	22	0.97	-0.23	0.93	24.39	594.81
70	24	0.94	0.34	0.91	-8.61	74.16
100	20	0.99	-0.17	0.94	21.39	457.48
97	24	0.99	-0.12	0.91	18.39	338.14
97	24	0.99	-0.12	0.91	18.39	338.14
92	17	1.00	-0.04	0.96	13.39	179.26
82	15	0.99	0.14	0.97	3.39	11.48
94	12	1.00	-0.07	0.98	15.39	236.81
91	16	1.00	-0.02	0.96	12.39	153.48
102	18	1.00	-0.22	0.95	23.39	547.03
96	18	1.00	-0.11	0.95	17.39	302.37
104	22	0.97	-0.25	1.00	25.39	644.59
66	20	0.91	0.41	0.94	-12.61	159.05
112	22	0.41	-0.38	0.93	33.39	1114.81
Total		14.10	2.84			5164.64

Cross Bed A

Cross Bed B

Azimuth A	Dip D	SINE A	COS A	COS D	(A1-A)	$(A1-A)^2$
75	27	0.97	0.26	0.89	-6.48	41.93
54	21	0.81	0.59	0.93	-27.48	754.88
67	18	0.92	0.39	0.95	-14.48	209.52
81	20	0.99	0.16	0.94	-0.48	0.23
80	16	0.99	0.17	0.96	-1.48	2.18
84	17	1.00	0.11	0.96	2.53	6.38
82	20	0.99	0.14	0.94	0.53	0.28
66	22	0.91	0.41	0.93	-15.48	239.49
94	28	1.00	-0.07	0.88	12.53	156.87
118	24	0.88	-0.47	0.91	36.53	1334.07
108	12	0.95	-0.31	0.98	26.53	703.57
84	19	1.00	0.11	0.95	2.53	6.375
79	16	0.98	0.19	0.96	-2.48	6.126
86	20	1.00	0.07	0.94	4.53	20.475
66	32	0.91	0.41	0.85	-15.48	239.45
Total		14.29	2.14			3721.83

Table 1.Paleocurrent results for the study location (Ogbunike).

Azimuth A	Dip D	Sine A	Cos A	Cos D	(A1-A)	$(A1-A)^2$
70	22	0.94	0.34	0.93	-4.92	24.12
76	20	0.97	0.24	0.94	1.08	1.17
56	22	0.84	0.56	0.93	-18.92	357.92
64	24	0.90	0.44	0.92	-10.92	119.22
84	28	1.00	0.11	0.88	9.08	82.47
76	28	0.97	0.24	0.88	1.08	1.17
74	28	0.96	0.28	0.88	-0.92	0.84
106	30	0.96	-0.28	0.87	31.08	966.05
66	30	0.91	0.47	0.87	-8.92	79.54
100	22	0.99	-0.17	0.93	25.08	629.07
98	20	0.99	-0.14	0.94	23.08	532.75
84	20	1.00	0.11	0.94	9.08	82.47
92	26	1.00	-0.04	0.90	17.08	291.77
90	22	1.00	0.00	0.93	15.08	227.45
84	20	1.00	0.11	0.95	9.08	82.47
Total		14.40	3.88			3478.55

Cross Bed C

Table 2. Paleocurent results for the study location and their environmental implications.

Locality	Outcrop	Formation	Pattern	MVA	Variance	Vector Strength	Environment
Ogbunike	Cross Bed A	Nanka	Unimodal	244.4	265.9	13.9°	Fluvial
Ogbunike	Cross Bed B	Nanka	Unimodal	235.8	368.9	13.8°	Fluvial
Ogbunike	Cross Bed C	Nanka	Unimodal	224.8	248.5	14.8°	Fluvial

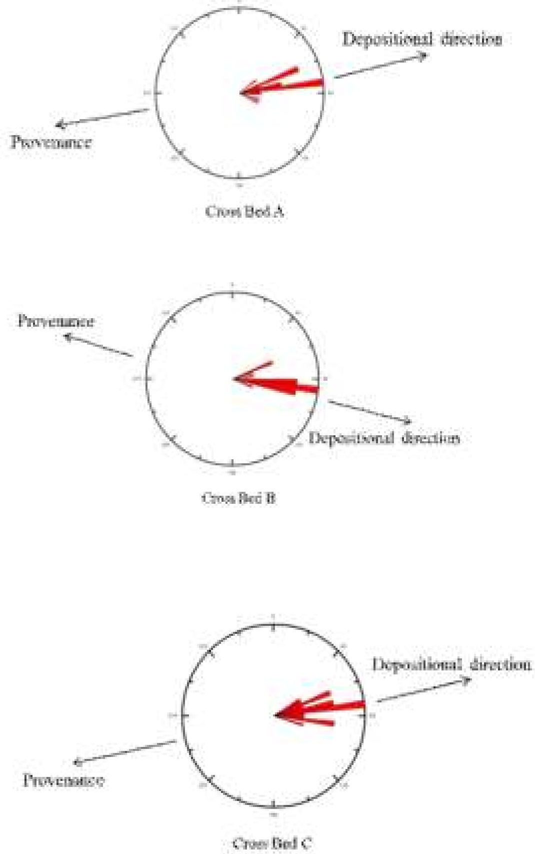

Fig.3. Rosette diagram showing provenance and depositional direction of cross beds A, B and C.

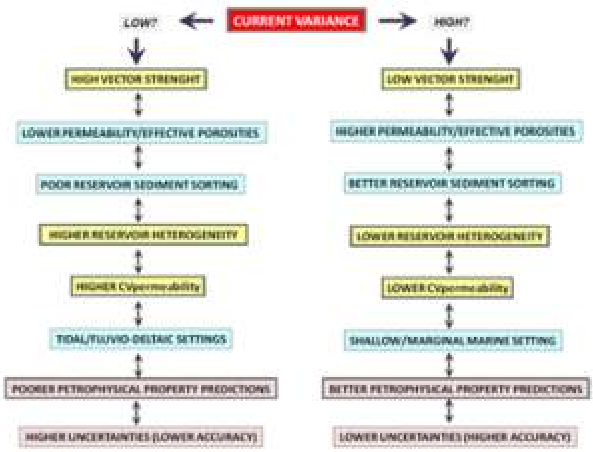

Figure 4.Flow chart for 'quick-look' reservoir evaluation given the paleocurrent data (After Obi *et al*, 2013).

GRANULOMETRIC ANALYSIS

Statistical size frequency parameters such as graphic mean, sorting, skewness and kurtosis were obtained from the plots using designated percentile values (Table 3). The ternary plots of sand, mud and gravel, and sand, silt and mud shows that the sediments are predominantly sands. Plots of particle size against class weight shows that the sediments are unimodal to polymodal. These suggest that the sediments were derived from different parent sources. The graphic mean of the distribution of sediment under investigation ranges from 1.4 to 2.3.

Table 3. Statistical parameters for Ogbunike sandstone

Sample	Mean (Mz)	Sorting	Skewness	Kurtosis	Mean	Sorting	Skewness	Kurtosis
M/OQ16	2.14	1.29	-0.30	1.65	Fine Sand	Poorly Sorted	Coarse Skewed	Very Leptokurtic
M/OQ17	1.40	1.30	0.010	1.04	Medium Sand	Poorly Sorted	Symmetrical	Mesokurtic
M/OQ08	2.27	0.86	-0.05	1.26	Fine Sand	Moderately Sorted	Symmetrical	Leptokurtic
M/OQ06	1.65	0.75	0.19	1.33	Medium Sand	Moderately Sorted	Fine Skewed	Leptokurtic
M/OQ14	1.41	0.80	-0.08	1.19	Medium Sand	Moderately Sorted	Symmetrical	Leptokurtic
M/OQ12	2.00	1.45	0.23	0.58	Medium Sand	Poorly Sorted	Fine Skewed	Very Platykurtic
M/OQ02	1.40	1.00	0.01	1.33	Medium Sand	Poorly Sorted	Symmetrical	Leptokurtic
M/OQ04	1.94	0.67	-0.11	1.26	Medium Sand	Moderately Sorted	Coarse Skewed	Leptokurtic
M/OQ10	1.65	0.75	0.19	1.33	Medium Sand	Moderately Sorted	Fine Skewed	Leptokurtic

This shows that 77.78% of the sediments are medium grained while 22.22% are fine grained suggesting a moderate to low energy of transportation medium (Folk and Ward, 1957). The sorting values range from 0.7 to 1.3 indicating that 55.56% of the samples are moderately sorted while 44.44% are poorly sorted. This implies fluvial origin. Skewness values range from -0.3 to +0.3 indicating 44.44% are symmetrical, 22.22% are coarsely skewed and 33.33% are coarsely skewed. This implies that 55.56% of the sediments are positively skewed suggesting fluvial origin. Bivariate plots of skewness versus sorting (figure 5a) and mean grain size versus sorting (figure 5b) also indicate that the environment of deposition is fluvial (Friedman 1967, Moiola and Weiser 1968).

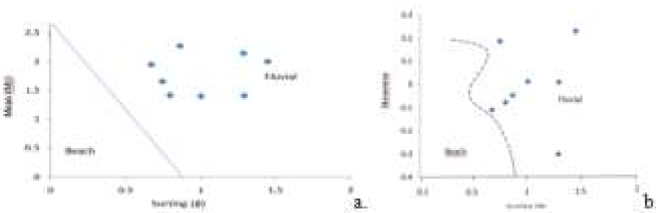

Figure 5.Graphs of Mean against Sorting (a) (After Miola and Waiser, 1977)

Skewness against Sorting (b) for the studied section (After Friedman, 1961).

Porosity

According to Teoh (2007), sedimentological studies have shown that porosity increases with increasing sorting. Increasing sorting also correlates with increasing permeability (Krumbein and Monk, 1942). A well-sorted reservoir sand contain grains that are about the same size and shape, while poorly sorted sands contain grains with different size and shape. The finer grains of the matrix block both the pores and throat passages within the framework for poorly sorted sediment but well-sorted sediment will have better porosity and permeability (Teoh, 2007). From the grain size data, the poor to moderate sorting of the samples suggest a poor to fair porosity for the sediment.

Reservoir Quality

The quality of the Ogbunike sandstone reservoir was studied using the coefficient of variance analysis. Essentially, the Cv represents the degree of variance of the statistical parameter. Distributions with CVv1 are considered low variance, while those with Cv>1 are considered high variance. According to Acra *et al*, 2014;Cv $\leq$ 0.5 is homogeneous or good sorting, Cv $\geq$ 0.5 $\leq$ 1 is heterogeneous or poor sorting, Cv $\geq$ 1 is very heterogeneous or very poor sorting. From the results (Table 4), the samples sorting ranges from heterogeneous (1.0) to homogeneous (0.4). The plot of coefficient of variance against mean grain size (figure 6) place the samples to be moderately sorted in more than a half of the sampled area. Hence the porosity is fair and the reservoir is heterogeneous on the average.

Table 4.Sorting and coefficient of variance of the Ogbunike sandstone.

Samples	Mean (Mz)	Sorting	Cv
M/OQ16	2.14	1.287	0.60
M/OQ17	1.40	1.29	0.92
M/OQ08	2.27	0.86	0.38
M/OQ06	1.65	0.75	0.45
M/OQ14	1.41	0.80	0.57
M/OQ12	2.00	1.45	0.73
M/OQ02	1.40	1.00	0.72
M/OQ04	2.00	0.67	0.35
M/OQ10	1.65	0.75	0.45

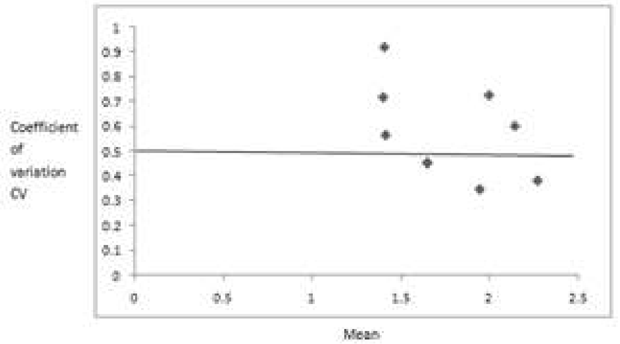

Figure 6.Coefficient of variance against mean grain size (Acra *et al*, 214).

Permeability

Permeability increases with increase in sorting of sediments (Krumbein and Monk, 1942). Qualitative description based on permeability values (North, 1985) adopted in this study is shown in table 3. From the empirical permeability data (table 4), the permeability of the sediments range from 0.727 to 3.736 suggesting poor to fair permeability based on permeability values of North, 1985.

Table 4.Qualitative description of permeability rocks in the study area obtained byuse of empirical formula(after Krumbrien and Monk, 1942).

Sample	Sorting	D50(um)	D50(mm)	K (mD)
M/OQ/16	1.287	192.5	1.925	0.998
M/OQ/17	1.292	375.5	3.755	3.736
M/OQ/08	0.864	202.6	2.026	0.727
M/OQ/06	0.746	331.7	3.317	1.683
M/OQ/14	0.797	367.8	3.678	2.774
M/OQ/12	1.448	322.0	3.220	3.079
M/OQ/02	1.004	379.3	3.793	2.962
M/OQ/04	0.672	256.5	2.565	0.907
M/OQ/10	0.746	331.7	3.317	1.683

HEAVY MINERAL ANALYSIS

From the analysis data (Table 5), the opaque minerals predominates the non-opaque. The opaque minerals constitute 73.90% while the non-opaque constitutes 26.10% on the average. The average ZTR% index is 52.87% with Tourmaline as the least abundant of ultra-stable minerals. This value indicates mature mineralogy of the sediments (Hubert, 1962). Figures 7 and 8 shows the abundance of the heavy minerals and ternary plot of ZTR respectively. The abundance of tourmaline and zircon in the heavy mineral suite suggest prolonged abrasion, chemical alteration and reworking of minerals from older sediments. The presence of garnet suggest plutonic source, epidote suggest metamorphic or hydrothermal source and apatite suggest basic to acid plutonic source. These suggest plutonic, metamorphic and older sediments sources for the sediments (provenance). These sources could be the younger granites (plutonic), Oban massif (metamorphic) and older sediments of the Benue Trough.

Table 5.Modal estimation of heavy mineral distribution.

Sample No.	Zircon (Z)	Tourmaline (T)	Rutile (R)	Staurolite (S)	Sillimanite (Si)	Garnet (G)	Apatite (A)	Epidote (E)	Opaque (Op)	Non-Opaque	ZTR Index (%)
MOQ02	6	4	12	12	2	1	-	1	88	38	57.9
MOQ04	4	3	7	11	1	2	-	2	76	30	46.7
MOQ06	6	4	7	10	1	1	1	1	93	31	54.8
MOQ08	7	4	5	10	1	2	1	1	114	31	51.6
MOQ12	5	6	9	9	1	2	1	2	72	34	58.8
MOQ14	4	3	7	11	1	2	1	2	75	30	46.7
MOQ16	6	4	7	11	1	1	1	1	93	31	54.8
MOQ17	7	4	5	10	1	2	1	1	114	31	51.6
Total	45	32	59	84	9	13	6	11	725	256	423
%									73.9	26.1	52.8

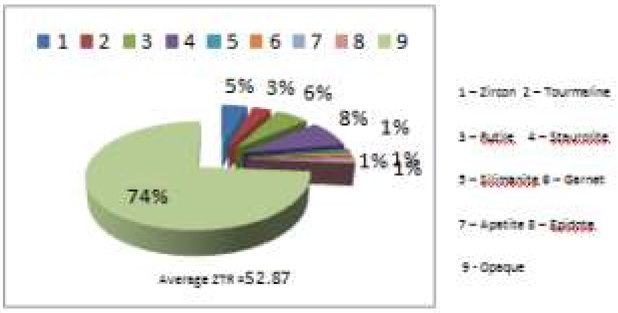

Figure 7. Abundance of heavy minerals in Ogbunike sandstone

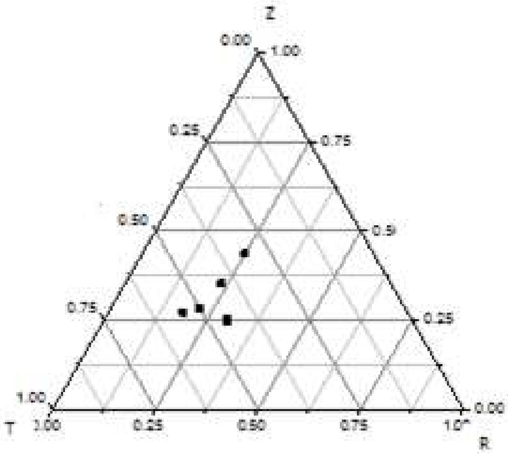

Figure 8.Tenary plot of average ZTR index.

CONCLUSION

The integrated sedimentology field study and inorganic geochemical analyses of the Eocene Nanka Formation at Ogbunike type locality, reveals that the outcrop consist of ironstone/sandstone, shale, sandstone, interstratified calcareous clay/mudstone and heterolithic sandstone sediments which are medium to fine grained. The outcrop is laterally extensive (about 82m) with a vertical thickness of about 14.78m.

The paleocurrent analysis shows a dominant polar-unimodal orientation or pattern with vector strength (mean of 14.18o) of high dispersion. The primary mode is in the Northeast direction approximately and the secondary mode in the southwest direction which shows the types of cross bedding that occurs in the study area. These results agree with the N-S regional paleocurrent trend established for the Anambra basin and in the study area. These unimodalpaleocurrent patterns are diagnostic of fluvial environment. The rose diagrams also suggest Northwest and Southwest provenance for the sediments. Azimuths of NE-SW and NW-SE directions described the paleocurrents of the formation. The variance is low and ranges from 248.5 to 368.9 and this indicates a fluvial environment. The low variance also suggests high vector strength, lower permeability and effective porosities, poor reservoir sediment sorting and higher reservoir heterogeneity.

Granulometric analysis identified the sediments to be bimodal to polymodal suggesting different parent sources, poorly to moderately sorted, predominantly positively skewed and leptokurtic. These suggest fluvial depositional environment and moderate to low energy of transportation medium. The poor to moderate sorting suggest poor to fair porosity, poor to fair permeability and a heterogeneous reservoir unit.

The heavy mineral suite using ZTR index supports the mineralogical maturity. This also suggests plutonic, metamorphic and recycled older sediments source origins (provenance)for the sediments.

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