Lithofacies and Textural Attributes of the NankaSandstone (Eocene): Proxies for evaluating the Depositional Environment and Reservoir Quality

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Abstract

The result of the lithofacies characterization, textural analysis using univariate, bivariate and multivariate analyses of environmentally sensitive parameters of the Nanka Sandstone show that the sandstone was deposited by tidal processes within a shallow, marine agitated environment, possibly the foreshore to upper shoreface setting. The sandstone is dominated by fine – medium grained, moderately sorted sandstones with clay-draped cross beds, reactivation structures, flaser beds, sigmoidal foreset laminations/beds and tidal bundles as well as *Ophiomorpha* and *chondrites*isp burrows. Porosity and permeability assessment of the sandstones using the empirical equation of Hazen showed average porosity and permeability values of 0.43 and 8.45m/d respectively for the Sandstone. The low permeability, in spite of the good porosity, is attributed to the high content of clays as drapes, flaser beds as well as disseminations in the sandstone.

Keywords: Lithofacies, Grain size, Reservoir, Sandstone, Clay drapes.

1   Introduction

The Nanka Sandstone (Eocene) is a friable sandstone facies of the Ameki Group representing the outcropping/up dip equivalent of the sub-surface Agbada Formation in the northern Niger Delta Basin. It overlies the Imo Formation (Paleocene) and outcrops in an area east of the Niger River underlying Awka, Nanka and Orlu area in southeast Nigeria. Nwajide (1979, 1980, 2013) studied the Nanka Sandstone and described it as a loose sand facies of the Ameki Group. The sandstone consists of fine to coarse grained, sub-rounded to sub-angular quartz arenite with poor cementing material. Gully erosion is a prevalent hazard as the loose sand are easily eroded, culminating gulley's in deep Nanka, Agulu, Orlu, Nnobi, Oraukwu, Alor and Nnewi areas.

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Grain size statistical analysis by sieve method have been used to infer sedimentary environments (Friedman, 1967; Moiola and Weiser, 1968;). Grain size distribution reflects both the fluidity and energetic factors of depositional media (Sahu, 1964; Pettijohn, 1975). It is also an established fact that grain sizes of clastic sediments are related to the physical characteristics of the depositional environments, especially the dynamic forces operating during deposition (Wenworth, 1992; Krumbein and Pettijohn 1938; Visher, 1969; Tucker and Vacher, 1980; McLaren, 1981; Forrest and Clark, 1989; and Sahu 1964;). Variations in textural characteristics such as grain size and sorting are largely dependent upon depositional processes, such as energy conditions and provenance of the sediments (Pettijohn, 1975). Textural characteristics could therefore be used to infer depositional environment. Sedimentary environments have been interpreted using lithology, sedimentary structures, textures, fossil content and stacking pattern of beds (Walker, 1984; Nichols, 2009). Based on lithofacies and textural parameters, it is always possible to reconstruct the palaeoenvironment of deposition (Wacher, 1979; Reading, 1978).

The purpose of this study, is to use textural parameters from sieve analysis, lithofacies and stacking pattern to interpret the depositional environment of the Nanka Sandstone outcropping at Umunya and to estimate the porosity and permeability of the rocks using the Hazen's (1982) empirical equations. Folk and Ward (1957) Inclusive Graphic Measures and Moment Measures (Friedman, 1967) were employed to evaluate textural parameters such as mean, standard deviation, skewness, mean cubed deviation and cubed standard deviation. As independent functions, bivariate or multivariate functions, these parameters have been found to be effective in discrimination of depositional environment. Reservoir hydraulic properties such as porosity and permeability are related to the depositional environments and processes (Reijers, 1996). While porosity depends on sorting (standard deviation), permeability is dependent on grain size. Using these textural parameters, porosity and permeability of the Nanka Sandstone facies were estimated.
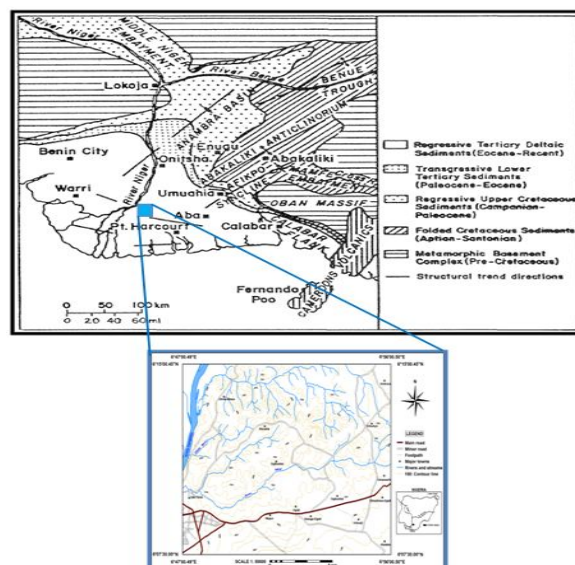

Figure 1:Regional geologic map of south eastern Nigeria showing location of thestudy area.

2   Geologic Setting

The early Cretaceous break-up of the South American and the African Plates led to the opening of the South Atlantic and installation of the Benue Trough in Southern Nigeria (Burke, 1976). Sedimentation in Southern Nigeria sedimentary basins was related to three major tectonic phases, giving rise to three successive depocentres/basins (Murat, 1972). The first phase (Albian-Connacian), featured the opening of the Benue Trough or rift and deposition of the Asu River Group, Odukpani Formation, Eze-Aku Group and Awgu Group in Southern Benue Trough. The second phase started after the Santonianepierogenic tectonics which folded and terminated sedimentation in the Southern Benue Trough and installed the Anambra Basin. The sediment fill of the Anambra Basin comprise the Nkporo Group conformably overlain by the Sandstone and Nsukka Formation. The third phase started when the Anambra Basin filled up and the Niger Delta started to prograde from the Paleocene. The Imo Formation and the Ameki Group were deposited in the Northern Delta in the Paleocene-Eocene period. Continued progradation resulted in deposition of the Ogwashi-Asaba and the Benin Formation from Oligocene to Miocene. Figure 1 displays the geologic map of South-eastern Nigeria showing the study area.

3   Materials and Methods

Outcrop section of the Nanka Sandstone at Umunya, was described with respect to lithofacies parameter such as lithology, sedimentary structures (physical and biogenic), texture, bed thickness and contact type. Eight (8) representative sandstones samples from the section were sieved (using a sieve nest of ½ phi interval (ASTM), on a digital shaker, for 15 minutes and described using Folk and Ward (1957) Inclusive Graphic Measures and Moment Measures (Friedman, 1967, Freidman and Sanders, 1978). Grain size statistical parameters such as mean, standard deviation, skewness, mean cubed deviation and cubed standard deviation were calculated using critical percentile from the cumulative frequency graphs. These were used as independent function or combined in bivariate or multivariate analysis to interpret the depositional environments. Empirical porosity and permeability estimates were also performed using the grain size distribution data and applying the Hazen (1982) equation given as:

$$K \;=\; \frac{g}{v}.\, 6x10^{-4} \left\lfloor 1+10\left(n-0.26\right)\right\rfloor d_{10}^{2} \tag{1}$$

Where:
K= Hydraulic conductivity,
g= Acceleration due to gravity,
d_{10} = effective grain diameter,
v = Kinematic viscosity for a given temperature,
(n) = porosity function.

These calculations were made using kinematic viscosity of $8.931*10^{-7}$ at temperature of 25^{oc}, acceleration due to gravity of $9.8m/s^2$ and grain diameter at 10th percentile obtained

from the cumulative curve of Folk and Ward (1987). The porosity (n) employed for this study is given by

$$n \; = \; 0.255 \left(1 + 0.83^{U} \right) \tag{2}$$

Where U, is the coefficient of grain uniformity represented by Hazen (1911) as a ratio:

$$U \;\; = \;\; \frac{d_{60}}{d_{10}} \tag{3}$$

d_{60} and d_{10} represents the grain diameter in mm, at 60% and 10% in Folk and Ward (1957) cumulative graph. The coefficient of uniformity defines the homogeneity of a sample of unconsolidated sediment.

4 Results

4.1 Lithofacies Characterization

In order to interpret depositional environments of ancient sedimentary rocks, careful logging and accurate characterization of lithologic variability, sedimentary structures, paleocurrent, fossil content, and geometry of sedimentary unit have been variously employed (Srivasta 2005; Le Blank 1972; Reineck and singh (1980); Selly (1972); Readings (1986); Walker (1984); and Nichols (2009). Seven (7) lithofacies were identified in the Nanka Sandstone outcropping at Umunya   as follows: (1) Fine grained, planar cross-bedded Sandstone lithofacies (2) Very fine grained, parallel/ripple laminated sandstone lithofacies, (3) laminated, clay stone lithofacies, (4) Fine-medium grained, cross bedded sandstone lithofacies (5) Sand-dominant heterolithiclithofacies. (6) Ripple laminated very fine grained sandstone lithofacies. (7) Clay dominant heterolithiclithofacies.

4.1.1   Fine grained, planer cross-bedded sandstone (*Lithofacies A*)

This consists of fine grained sandstone, moderately sorted and clayey. This unit is planar cross bedded with sigmoidal and clay draped foreset beds. The crossbed azimuth is dominantly to the NE. Reactivation surfaces modify the cross bedded sets and laterally separates them into several tidal bundles (Fig 2A). *Ophiomorphaisp* and *chondritesisp* burrows (Fig 2B) are common. Clay chips or rip-up clasts are present. The bed thickness varies from 0.4-0.5m separated by 0.1-0.25m thick master beds.

4.1.2   Very fine grained, parallel/ripple laminated clayey sandstone (*Lithofacies B*)

This lithofacies comprises very fine grained, horizontal bedded and ripple sandstone with moderate sorting. The average thickness varies from 0.10-1.30m. It is finely laminated with clay ripple laminations. These beds form master beds (Nwajide 2013) separating the cross bedded units. The beds are attributed to the coalescence of clay drapes in subjacent or superjacent beds (Nwajide 2013).

4.1.3 Laminated claystone (*Lithofacies C*)

This lithofacies comprise of whitish clean laminated claystone. It exhibits platy fissility and dominated by micaceous clay mineral and silt sized quartz.

4.1.4 Fine-medium grained, cross bedded sandstone (*Lithofacies D*)

This lithofacies comprise of thickly bedded coarse sandstone with several other finer beds towards the top. It is cross bedded (trough or planar), well sorted and brownish in colour. The crossbed azimuth is dominantly to the southwest (SW = 216°) and the basal contact is erosional.

4.1.5 Sand dominant heterolithic (*Lithofacies E)*

This facies is characterized by fine-medium grained sand at the bottom with alternating clay beds and fine sandstones at the top.

4.1.6 Ripple laminated very fine grained sandstone (*lithofacies F*)

This lithofacies consists of very fine grained sandstone and silt. The sandstone is brownish in colour and contains wavy ripple laminations or low amplitude. (Fig. 2E).

4.1.7 Clay dominant heterolithiclithofacies (*Lithofacies G*)

This facies comprises claystoneinterbedded with sub-ordinate very fine grained sandstone beds. The main characteristics is the prevalence of wavy ripple and convolute laminations. (Fig. 2D).

Figure 2: A. Clay draped foresets, Reactivation surface, crossbeds with ripple lamination (B) Ophiomorpha burrows (C) Average thickness of crossbed (D) Claystone bed bounded by sandstone (E)Siltstone (F) Heterolithic stratification showing parallel bedding.
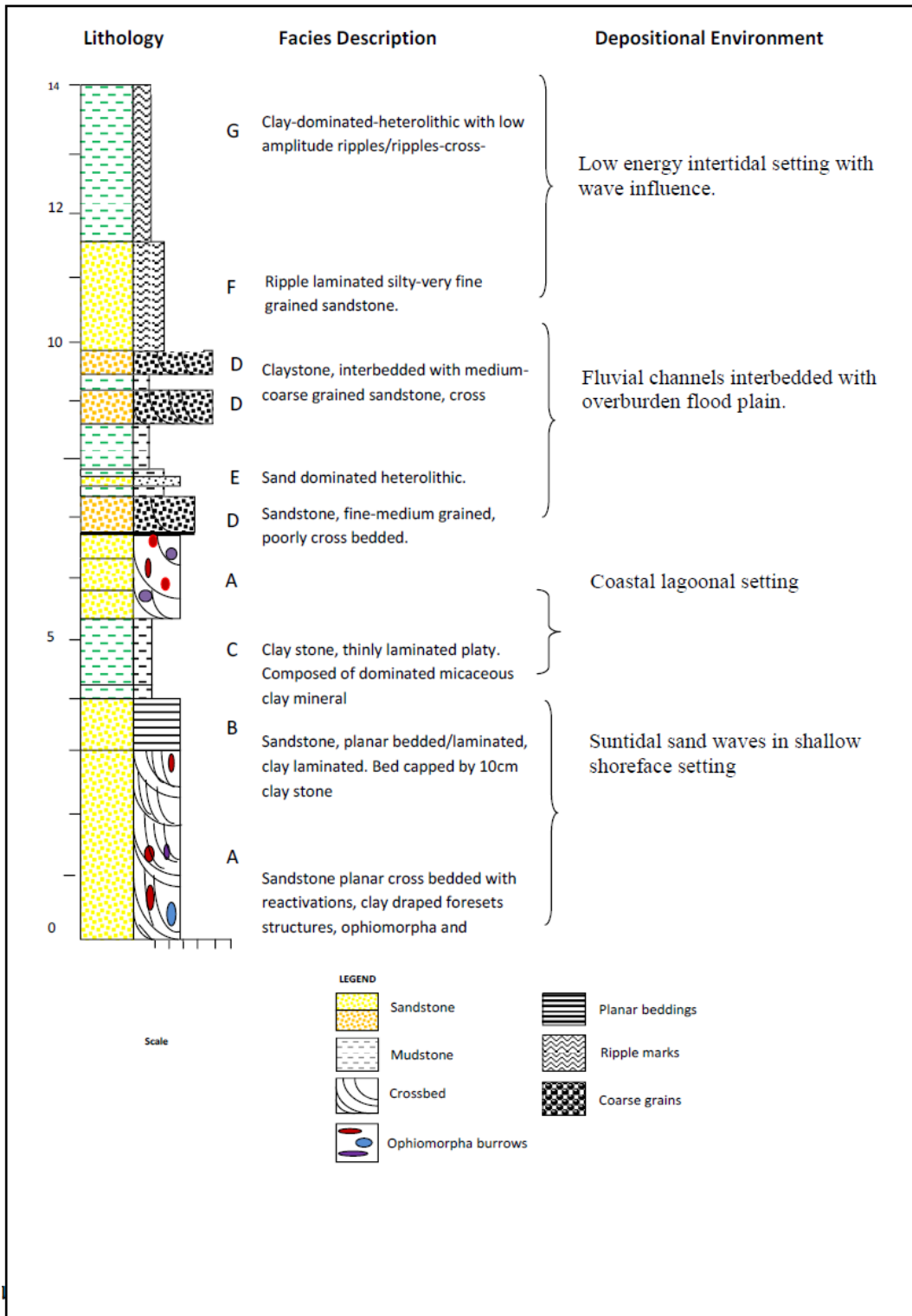
Figure 3: Log section displaying lithofacies and their corresponding environments.

4.2 Grain Size Analysis

Tables 1 and 2 show the descriptive statistics derived using Folk and Ward (1957) and Moment statistics respectively (Freidman 1967). The results indicate that the Nanka Sandstone is fine grained (2.17-2.55Φ) and moderately well sorted (0.54-1.00Φ). The sand exhibit negative skewness (-0.80 to -0.20) except for samples NANSM2 and NANSM 8 which show nearly symmetrical skewness (0.03-0.04Φ). The predominantly negative and near symmetrical skewness of the sandstone suggest deposition in the near-shore regime with high energy (Okoro, 1995). Except for sample NANSM8 which appears very leptokurtic, all other samples are leptokurtic (Table 3). The plot of mean cubed deviation against cubed standard deviation (Friedman, 1967) shows that the Nanka Sandstone was deposited in a marine environment (Figure 6).

Table 1: Shows descriptive statistical analysis for the grain size statistical parameters

SAMPLE NUMBER	MEAN	MEDIAN	MODE	STANDARD DEVIATION	SKEWNESS	KURTOSIS (K)
NANSM1	2.28	2.30	0.13	0.90	-0.02	1.19
NANSM2	2.45	2.45	0.13	0.71	0.03	1.35
NANSM3	2.29	2.32	0.14	0.75	-0.05	1.32
NANSM4	2.46	2.48	0.13	0.82	-0.06	1.42
NANSM5	2.48	2.49	0.13	0.66	-0.04	1.42
NANSM6	2.22	2.25	0.11	1.00	-0.80	1.00
NANSM7	2.55	2.54	0.13	0.54	-0.04	1.37
NANSM8	2.17	1.71	0.21	0.72	0.04	1.55
AVERAGE	2.36	2.32	0.14	0.76	-0.12	1.33

Table 2: Moment parameters calculated according to Friedman (1967)

SAMPLE NUMBER	MEAN	MEDIAN	MODE	STANDARD DEVIATION	SKEWNESS	KURTOSIS (K)
NANSM1	2.28	2.30	0.13	0.90	-0.02	1.19
NANSM2	2.45	2.45	0.13	0.71	0.03	1.35
NANSM3	2.29	2.32	0.14	0.75	-0.05	1.32
NANSM4	2.46	2.48	0.13	0.82	-0.06	1.42
NANSM5	2.48	2.49	0.13	0.66	-0.04	1.42
NANSM6	2.22	2.25	0.11	1.00	-0.80	1.00
NANSM7	2.55	2.54	0.13	0.54	-0.04	1.37
NANSM8	2.17	1.71	0.21	0.72	0.04	1.55
AVERAGE	2.36	2.32	0.14	0.76	-0.12	1.33

Table 3: Summary of grain size statistical parameters for this study

SAMPLE NUMBER	INCLUSIVE GRAPHIC MEAN (MZ)	INCLUSIVE GRAPHIC STANDARD DEVIATION (Σi)	INCLUSIVE GRAPHIC SKEWNESS (SKI)	INCLUSIVE GRAPHIC KURTOSIS (KG)
NANSM1	2.8 (Fine sand)	0.9 (Moderately well sorted)	-0.02 (Very negative skewed)	1.19 (Leptokurtic)
NANSM2	2.45 (Fine sand)	0.71(Moderately well sorted)	0.03 (Very negative skewed)	1.35 (Leptokurtic)
NANSM3	2.29 (Fine sand)	0.75 (Moderately well sorted)	-0.05 (Very negative skewed)	1.32 (Leptokurtic)
NANSM4	2.46 (Fine sand)	0.82 (Moderately well sorted)	-0.06 (Very negative skewed)	1.42 (Leptokurtic)
NANSM5	2.48(Fine sand)	0.66 (Moderately well sorted)	-0.04 (Very skewed)	1.42 (Leptokurtic)
NANSM6	2.22 (Fine sand)	1.00 (Moderately well sorted)	-0.8 (Negative skewed)	1.00 (Leptokurtic)
NANSM7	2.55 (Fine sand)	0.54 (Moderately well sorted)	-0.04(Negative skewed)	1.37 (Leptokurtic)
NANSM8	2.17 (Fine sand)	0.72 (Moderately well sorted)	0.04 (Negative symmetrical)	1.55 (Very Leptokurtic)

4.2.1 Multivariate and Bivariant Scatter Analyses

Multivariate discriminate functions (Y_1, Y_2 Y_3) proposed by Sahu (1964), were applied to the grain size data in order to characterize the depositional setting of the sediments (Table 4).

I. For the discrimination between Aeolian process and littoral (intertidal zone) environment, the following equations were used:

Y_1= -3.5688Mz + 3.701σI2-2.0766SK + 3.1135KG (Sahu 1964).

Where Mz is the mean grain size, σI is the inclusive graphic standard deviation (sorting), SK_1 is the skewness, and KG is the graphic kurtosis. When Y_1 is less than -2.7411, Aeolian depositionis indicated, whereasif Y_1 is greater than -2.7411, a beach environment is suggested. The value of Y1 calculated from the Nanka Sandstone varies from -3.68 to 0.55 (Table 4). Over 66% of the sands have Y_1 >2.7411. Therefore the sands may have been deposited dominantly by beach processes.

II. For the discrimination between beach (back shore) and shallow agitated marine environment (sub-tidal environment), the following equation was used:

Y_2 = 15.6534Mz + 65.7091$σ_I^2$ + 18.10871SK$_1$ + 18.5043KG (Sahu 1964)

If the value of Y_2 is less than 65.3650, beach deposition is suggested. If it is greater than 65.3650, a shallow agitated marine environment is likely. The average values of Y_2 calculated for the Nanka Sandstone indicates that 100% of the Sandstone was deposited in shallow agitated marine environment (Table 4).

III. For the discrimination between shallow marine and the fluvial environment, the following equation was used:

$$Y_3 = 0.2852Mz - 8.7604\sigma_I^2 - 4.8932SK_1 + 0.0482KG \text{ (Sahu 1964)}$$

If Y_3 is less than -7.419, the sand is identified as a fluvio-deltaic deposit, and if greater than -7,419 the sample is identified as a shallow marine deposit. Following the result of this analysis, Y_3 ranges from -0.69 to -1.55 suggestive of deposition in shallow marine environment.

Plotting of the three discriminate functions (Y_1, Y_2 and Y_3) as bivariate scatter plots was used to improve the success rate and refinement of the discrimination of the depositional environment. Figure 4 shows the scatter plot of Y_1 and Y_2. Based on the classification of depositional environments using Y_2 vs. Y_1, graphs, over 60% samples are plotted within the field of beach/shallow marine environment. These graphs are divided into four fields (1) the Eolian processes/beach environment, (2) beach and littoral environment, (3) beach environment/shallow marine agitated deposition and (4) Eolian process/shallow agitated marine environment (Sahu 1964). A similar plot of Y_3 vs. Y_2 (Sahu, 1964) to distinguished fluvial and beach deposits, showed that the samples were plotted in the shallow marine/beach deposit field. Textural analysis of the Nanka Sandstone at Umunya shows that the sand represents deposits of shallow marine agitated environments.

Based on lithofacies and grain size distribution parameters therefore, the Nanka Sandstone was deposited in shallow marine tidal setting. This corroborates the interpretation of Nwajide (1979, 1980), that the Sandstone was deposited in a tidal environment.

Table 4: Shows the Discriminate Function and Environment of Deposition of Each sample.

| Y1	ENVIRONMENT OF DEPOSITION	Y2	ENVIRONMENT OF DEPOSITION	Y3	ENVIRONMENT OF DEPOSITION
-1.391971	Beach	110.5721	Shallow agitated marine	-6.290684	Shallow marine
-2.751833	Aeolian	96.729398	Shallow agitated marine	-3.763456	Shallow marine
-1.886066	Beach	96.163703	Shallow agitated marine	-3.944696	Shallow marine
-1.75341	Beach	107.72214	Shallow agitated marine	-4.806124	Shallow marine
-2.717686	Beach	93.284258	Shallow agitated marine	-2.883392	Shallow marine
0.553644	Beach	104.47827	Shallow agitated marine	-4.164696	Shallow marine
-3.678417	Aeolian	83.598416	Shallow agitated marine	-1.551768	Shallow marine
-1.076603	Beach	97.542559	Shallow agitated marine	-4.057852	Shallow marine
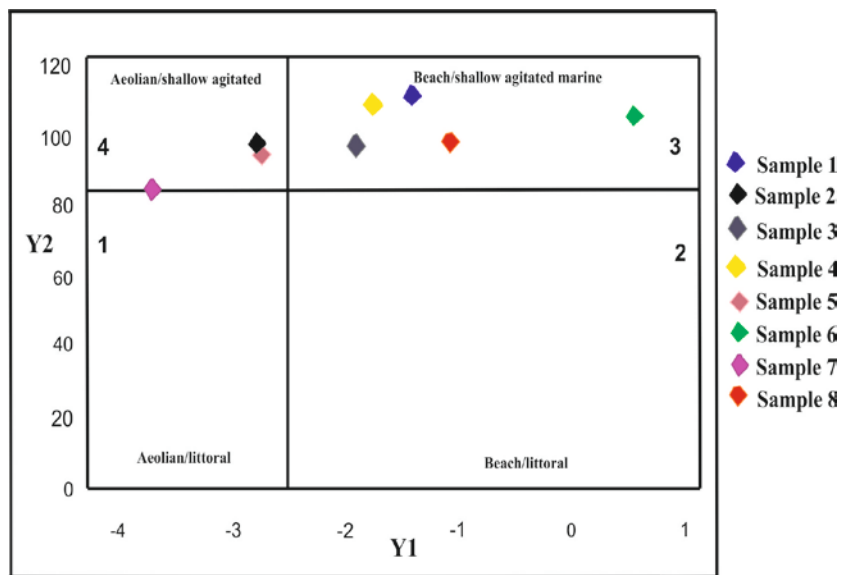
Figure 4: Bivariate plot of Y_2 against Y_1 for Nanka Sandstone using the template of Alsharhan and El-Sammak (2004)
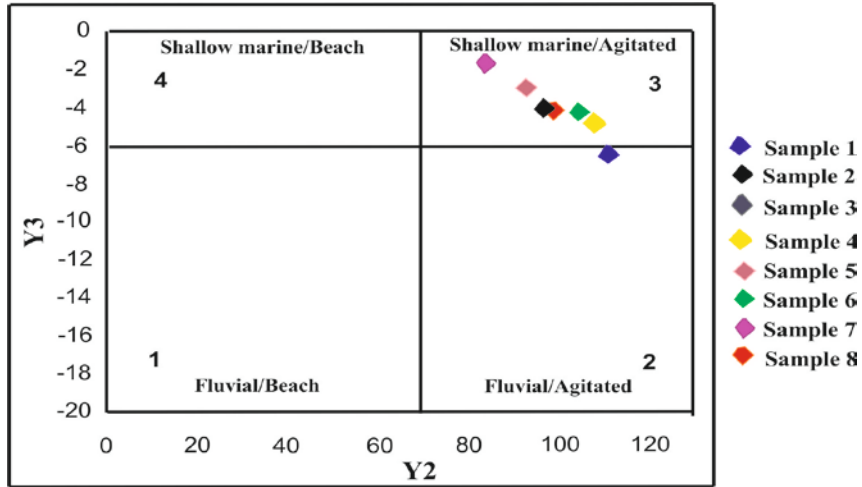
Figure 5: Bivariate plot of Y_2 against Y_1 for Nanka Sandstone using the template of Alsharhan and El-Sammak (2004)
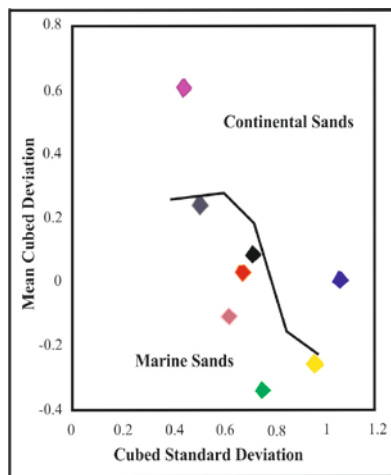

Figure 6: The plot of mean cubed deviation vs. cubed standard deviation of Nanka Sandstone
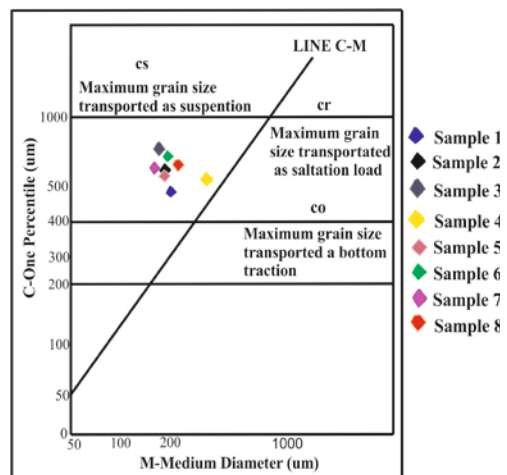
Figure 7: C-M pattern showing mechanism of deposition.

4.3 Paleocurrent Analysis

The azimuths of cross- beds were used to evaluate the dispersal pattern of the Nanka Sandstone. The result shows a dominant unimodalpaleocurrent pattern in the easterly direction (Table 5 and Figure 8). A secondary westerly mode appears to suggest a sub-ordinate/minor reverse flow to the west. The sediments were therefore possibly derived from a westerly located provenance and modified by tidal current. The dominant unimodal, low variance paleocurrent pattern suggests deposition by dominantly unidirectional currents.

Table 5: Shows Tallies of Cross bed Azimuths

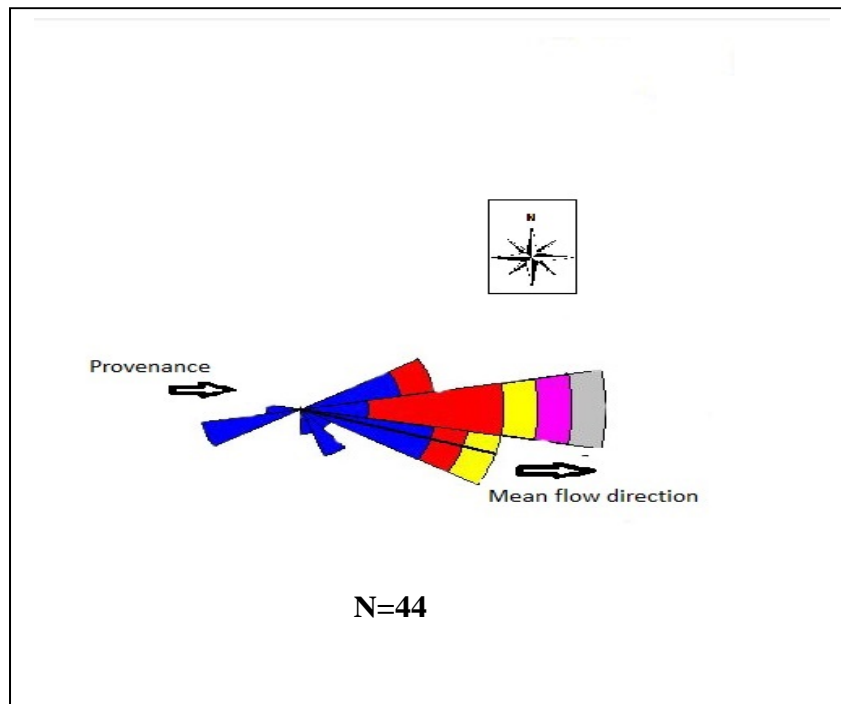| Class Interval (®)	Frequency	Frequency %
0-30	0	0
31-60	0	0
61-90	19	43.1
91-120	17	38.6
121-150	2	4.6
151-180	2	4.6
181-210	0	0
211-240	1	2.3
241-270	3	6.8
271-300	0	0
301-330	0	0
331-360	0	0
	∑f=44	∑f(%)=100

Figure 8:Paleocurrent pattern from cross bed azimuths in the Nanka Sandstone showing a bimodal pattern in the SE and SW direction in tidal environment

4.4 Reservoir Hydraulic Parameters of Nanka Sand

The most important parameters for reservoir quality assessment are porosity and permeability. The results of the calculated reservoir hydraulic parameters using Hazen (1982) empirical equation are shown in Table 6.

The porosity of the sandstone ranges from 0.42-0.44 with average values of 0.43 while permeability (k) ranges from 5.55-16.54m/d with average of 8.45m/d. This suggests that Nanka Sandstone of Umunya is a potential poor reservoir. The low permeability is

attributed to the presence of abundant clay-drapes, laminations and dispersed clay in the generally fine grained deposits.

Table 6: Shows Calculated Values of Porosity and Permeability Using Hazen Formula

SAMPLE NUMBER	POROSITY (n)	PERMEABILITY (k in m/d)
NANSM1	0.42	6.68
NANSM2	0.43	6.64
NANSM3	0.43	8.95
NANSM4	0.43	6.42
NANSM5	0.44	8.24
NANSM6	0.43	5.55
NANSM7	0.44	8.59
NANSM8	0.42	16.54
AVERAGE	0.43	8.45

5 Discussion and Conclusion

5.1 Discussion

The lithofacies and sedimentary structures of the Nanka Sandstone consists of abundant planar cross beddings with clay drapes and reactivation structures as well as parallel and ripple laminations which are suggestive of tidal sedimentation (Walker, 1984; Nwajide, 1979; Shammugam, 2003; Nichols 2009). The occurrence of *Ophiomorpha*isp burrows is suggestive of deposition in a high energy sub-tidal and intertidal flat environments (Nwajide and Hoque, 1979; Nwajide, 1980; Amajor, 1984; Mode, 1991). The *Ophiomorpha*has been useful in Cretaceous environmental studies in the Rocky Mountain area for several decades as an indicator of shallow-marine sedimentation. Although there are several variations, similar trace fossils are also found in Cretaceous, Tertiary and Quaternary sedimentary rocks in many places in the world (John and Robert, 2005). Boggs (1995) noted that sub-tidal and sand flats (lower intertidal) are characterized by deposition of cross bedded sands with flaser beddings and clay drapes as in the Nanka Sandstone. The alternation of sand and thin ripple laminated clay (heterolithicslithofacies F and G) are suggestive of mixed flat environment. Visser (1980) proposed that the presence of clay drapes and tidal bundles in cross bed sets is indicative of in-shore tidal environment of deposition. The grain size distribution parameters suggest deposition in a marine/beach setting. This is supported by the bivariate plot of the discriminate functions

(Y1, Y2 and Y3) of (Sahu 1964) which suggest deposition in shallow agitated marine environment.

5.2 Conclusion

Based on lithofacies and grain size distribution parameters, it has been established that the Nanka Sandstone in the study area was deposited in a shallow marine agitated environment, most likely a tidal/sub-tidal shore line environment. Reservoir quality assessment indicates that the sandstone has good porosity but, poor permeability due to the presence of abundant clay drapes and laminations which are deleterious to flow. The Sandstone in spite of its good porosity is therefore potentially a poor reservoir due to poor permeability.

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