Journal of Geosciences and Geomatics, 2019, Vol. 7, No. 4, 172-183
Available online at http://pubs.sciepub.com/jgg/7/4/2
Published by Science and Education Publishing
DOI:10.12691/jgg-7-4-2

Reservoir Potential, Environment of Deposition, Tectonic Setting, and Provenance of Rock Units in the Anambra Basin, Southeastern Nigeria

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Received May 09, 2019; Revised June 25, 2019; Accepted July 04, 2019

Abstract A total of eight (8) sandstone samples were subjected to sedimentological and inorganic geochemical analyses in the investigation of reservoir potential, environment of deposition, tectonic setting, and provenance of Campano-Maastrichtian rock units in Anambra Basin, southeastern Nigeria. Sedimentological studies reveal that samples of Owelli and Ajali Sandstones are coarse to medium grained, poorly sorted to moderately sorted sediments deposited in a fluvial environment. The heavy mineral assemblages made up of garnet, epidote and staurolite suggest a metamorphic source while tourmaline and zircon suggest igneous or metamorphic sources. The high maturity indices (58.6 to 71.4) as well as the high percentage of quartz (68 to 74%) suggest mature sandstones that can act as reservoir for generated hydrocarbon. The major oxides discriminate function diagram shows active passive margin for the sandstone samples. Quartzose sedimentary provenance was shown for the sediments which have been highly reworked from original igneous and metamorphic sources, possibly from Abakiliki uplift, Oban massif and/or Obudu basement rocks in the southeast. The high chemical index of alteration (averaging 93%) and the low ratio of K_2O/Al_2O_3 (0.02 to 0.11) in the sediments confirms sedimentary recycling and intensive source area weathering.

Keywords: *Sedimentological, inorganic geochemical analysis, reservoir potential, environment of deposition, Anambra Basin*

Cite This Article: Maju-Oyovwikowhe G E, and Imasuen I O, “Reservoir Potential, Environment of Deposition, Tectonic Setting, and Provenance of Rock Units in the Anambra Basin, Southeastern Nigeria.” *Journal of Geosciences and Geomatics*, vol. 7, no. 4 (2019): 172-183. doi: 10.12691/jgg-7-4-2.

1. Introduction

For a rock to act as a reservoir, it must possess two essential properties: it must have pores to contain the oil or gas, and the pores must be connected to allow the movement of fluids; in order words, the rock must have permeability. The rock must also be porous. These characteristics are satisfied by the common sedimentary rocks known as sandstones. Sandstones are arenaceous clastic sedimentary rocks, formed by lithification of sand beds. The size of the individual constituent sand grains vary between 2mm to 0.1 mm. Quartz is the chief mineral constituent of sandstones. However, other minerals are often present in small amounts. The cementing material may be siliceous, argillaceous, ferruginous or carbonate in nature.

The aim of this work is to evaluate the sedimentological properties of both the Ajali and the Owelli surface sandstones outcropping along Enugu-Portharcourt expressway to determine their environment of deposition, tectonic setting and reservoir potential.

1.1. Geology of the Study Area

The Anambra Basin is located to the Southwest of the Benue Trough that lies within the sedimentary terrain of Nigeria. The major sedimentary rock groups in Nigeria are terrigenous and were deposited from lower Cretaceous to Recent in seven sedimentary basins and troughs namely: Benue Trough, Sokoto Basin, Chad Basin, Niger Delta Basin, Bida Basin, Dahomey Basin and Anambra Basin. The Benue Trough and the Niger Delta Basin are marginal sag basins formed in response to tensional regimes accompanying the opening of the equatorial Atlantic Ocean while the other five basins were formed on the basement complex by sagging and/or faulting.

The Anambra Basin was formed in the late Cretaceous. It extends northward to the Benue Trough and forms a boundary with the Tertiary Niger Delta in the south. To the northwest, Anambra Basin is bordered by the rocks from the onshore part of West African miogeosyncline in Eastern Ghana, Togo, Benin and Western Nigeria. The sediments range in age from late Cretaceous to Recent. The Benin flank is joined at its northern end by Bida

Basin or middle Niger Embayment. To the southeast, the Anambra Basin is bounded by the Abakiliki Cretaceous fold belt of sediments that accumulated in the post-Santonian time.

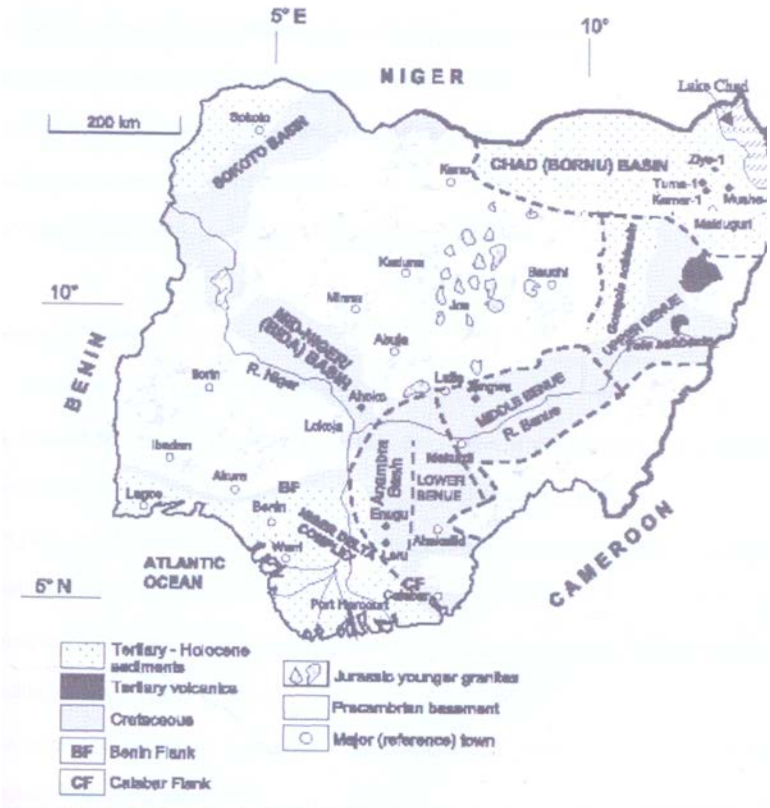

Figure 1. Geological Map of Nigeria showing the Location of Anambra Basin (adapted from Obaje *et. al.*, 2004)

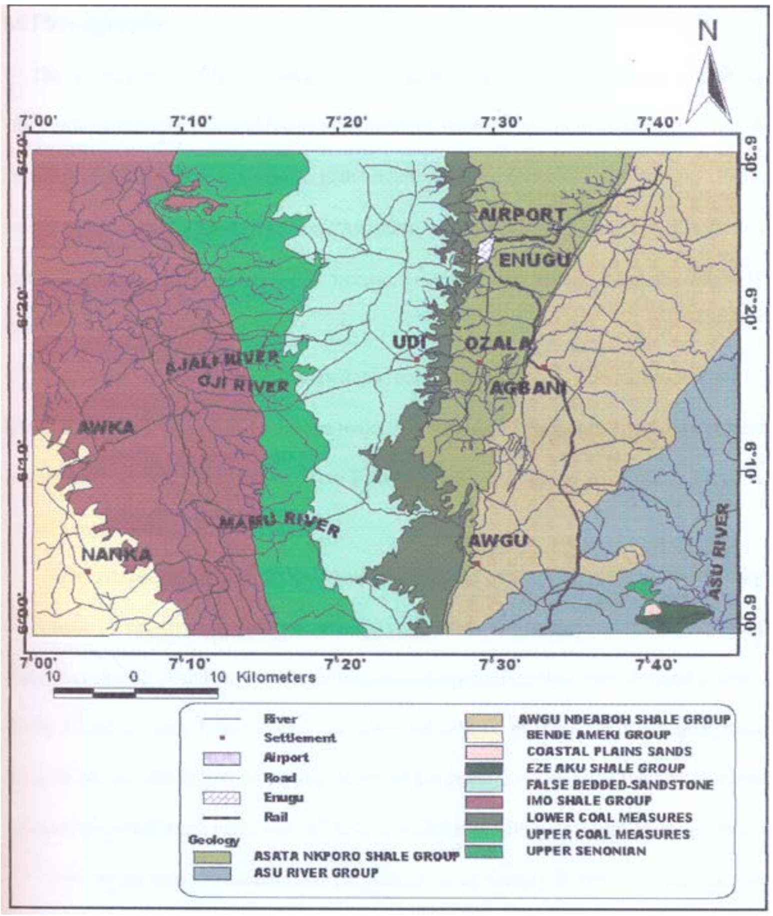

Figure 2. Geological Map of the Study Area (adapted from GSN: Geological Map of Enugu, sheet 72, 1st edition; Scale: 1:250,000)

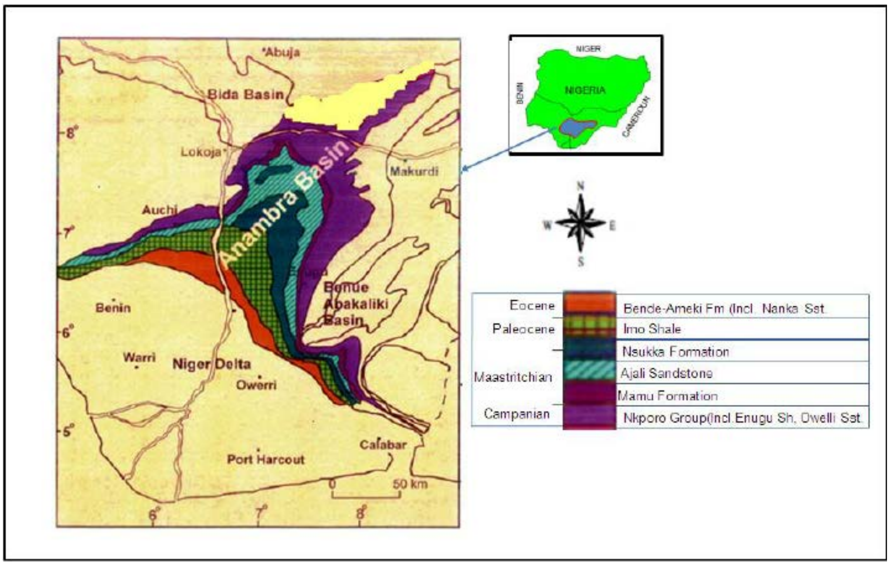

Figure 3. Stratigraphy of Anambra Basin

1.2. Stratigraphy of Anambra Basin

The Stratigraphy of the Anambra Basin is summarized in Figure 3.

2. Materials and Methods

2.1. Field Study

The field study was a one-week exercise and it involves an initial reconnaissance survey and then a detailed geological mapping of the study area. It was aimed at identifying the rock types along road cuts, sedimentary structures, textural features and establishing the stratigraphic succession of the rocks based on their field relationships. Thickness and lateral extent of beds were noted and photographs of important features on outcrops were taken. Rock samples from studied outcrops were collected and labeled for further laboratory studies. Lithologs were drawn right on the field and later modified using Corel Draw computer software.

The equipment and items used during the field exercise include a base map (scale 1:25,000), measuring tape, compass-clinometer, digital camera, geological hammer, chisel and sample bags. Others are field notebook, biro, pencil, eraser, meter rule, masking tape and marker. Study materials include fresh outcrop of sandstone samples obtained from two (2) locations within Enugu and environs.

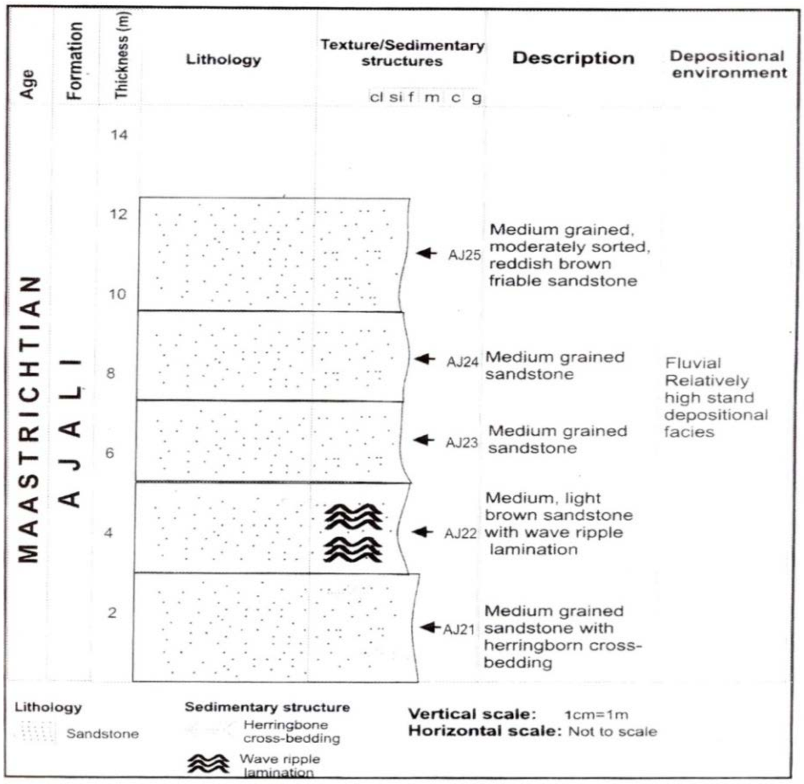

Figure 4. Litholog of Ajali Sandstone exposed at a road cut about 5km from Onyeama mine (between 9th Mile and Onyeama mine)

Figure 5. Field Photograph of Ajali Sandstone exposed at a road cut about 5km from Onyeama mine (between 9t Mile and Onyeama mine)

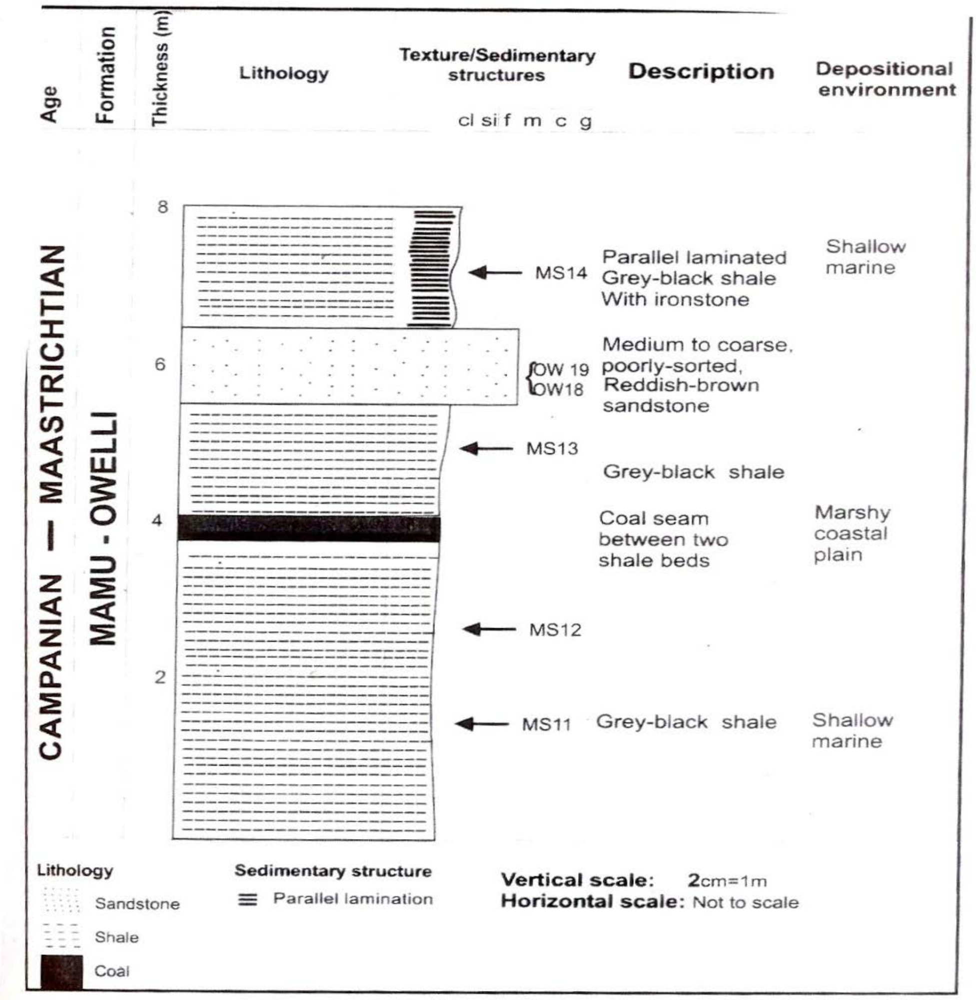

Figure 6. Owelli Formation at Agbogugu-Ihe junction along Enugu-Portharcourt expressway (26km south of Enugu)

2.2. Laboratory Techniques

2.2.1. Granulometric Analysis

Each sample was thoroughly mixed and a representative fraction obtained by coning and quartering. 100g of the fraction was weighed on a metre balance and poured onto the top sieve of a nest of sieves of 0.5Φ intervals. The sieve was capped and the stack set on a Ro-tap mechanical sieve shaker for a constant time of 15 minutes. The stack was then removed and the sediment in each successive sieve emptied onto a piece of glaze paper. The fractions of grains retained in the sieves and pans were then weighed and the weights recorded. The percentages of these weights, as well as their cumulative weights and cumulative weight percentages were determined and tabulated. Cumulative frequency curves and histograms were plotted on log probability paper for each sample. Grain sizes corresponding to the 5th, 16th, 25th, 50th, 75th, 84th and 95th percentiles were obtained and used to calculate the graphic mean, standard deviation (sorting), inclusive graphic skewness and graphic kurtosis. The formulas proposed by [5] were adopted in the above calculations.

2.2.2. Petrographic Analysis

Thin sections of the samples were prepared based on the method described by [9]. The loosely consolidated sandstone samples were impregnated with resin before cutting while the indurated samples were thin sectioned directly. Each of the samples was mounted on a glass slide using Canada balsam. The mounted sample was then ground on a lap wheel with a coarse abrasive and later washed with water. These was followed by manual grinding with sludge of fine abrasive on a glass plate until the slide was fine or thin enough for individual mineral identification. The slide was then washed with water and allowed to dry before covering with a cover slip. The thin section slides were examined with the aid of a petrographic microscope. Different minerals were identified and their relative abundance estimated. This was based on the optical properties of the minerals.

2.2.3. Heavy Mineral Separation

Five (5) grams of sandstone samples were gently crushed and allowed to pass through a sieve of mesh size 0.25mm. The samples were treated with dilute HCL for about two minutes to remove carbonates. Washing was done with distilled water to remove any acid and the samples were dried on a hot plate. The gravity settling technique was used for the separation of the heavy minerals. The tools and reagents used are dilute HCL, acetone, bromoform, Canada balsam, funnel, filter paper and slides. The dried sample was poured into the separating funnel that is partly filled with bromoform. The mixture was stirred and then allowed to settle at the stem of the funnel. The separating funnel tap was then opened to allow only the heavy minerals that settled to fall into a filter paper fitted into a glass funnel in a conical flask. The heavy minerals collected were then washed with acetone to remove the effect of bromoform and to allow quick drying. Then the heavy minerals were mounted on a slide with Canada balsam and dried on a hot plate to ensure even spread of the balsam. The heavy minerals were examined and identified, on the basis of their unique optical properties, with the aid of a petrographic microscope. The number, size and shape of the different opaque and non-opaque minerals were noted. Photomicrographs of the heavy minerals were also taken.

The maturity index (ZTR) was calculated using the [8] formula as shown below:

$$ZTR\ index = \frac{Zircon + Tourmaline + Rutile}{Non - opaque} x\,100.$$

The quality of a reservoir is defined by its hydrocarbon storage capacity and deliverability. The hydrocarbon storage capacity is characterized by the effective porosity and the size of the reservoir, whereas the deliverability is a function of the permeability. Point to note here is that the clay minerals in the sandstone were not studied in this work, because it's beyond the scope of this study. This work does not entail reservoir quality analysis which entails clay mineral studies. Emphasis was based on reservoir potential of the sandstones in the studied outcrops. This research was carried out to determine if the sandstones has the potential of a reservoir rock. Thus, emphasis was based on the maturity indices as well as the mineralogical and inorganic geochemistry analysis in this study.

2.2.4. Inorganic Geochemistry Analysis

Atomic Absorption Spectrophotometry was employed in this study. It is based on the fact that atoms of an element can absorb electromagnetic radiation and that the wavelength of the light absorbed is specific to each element. The spectrophotometer is made up of an atomizing device, a light source and a detector. There is a lowering of response in the detector during the atomization of a sample in a beam of light. So atomic absorption can be calibrated and is sensitive to the ppm level. The samples were subjected to Atomic Absorption Spectrophotometry (AA-300 spectrometer) following digestion for 12 hours at 100^{0}C with hydrochloric and hydrofluoric acids in closed Teflon liners placed in stainless steel cases. The major element oxides SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, MnO, Na_2O and K_2O in (wt %) and trace elements (Ni, Cu, Zn, Pb, Cr and Ba (parts per million) were determined.

3. Results and Discussion

Generally, the ternary plot of framework composition of the Owelli and Ajali sandstones is suggestive of plutonic humid paleoclimate in the depositional environment. The sandstones are poorly sorted to moderately sorted and cross-bedded suggesting fluvial sediments. Bivariate scatter plots of inclusive graphic skewness against sorting and mean against sorting also indicate a fluvial depositional environment of the sandstones. Plots of cumulative weight percent against grain size suggest mainly fluvial environment for Ajali Sandstone and deltaic environment for Owelli Sandstone. Therefore the Ajali and Owelli sandstones were deposited in a fluvial environment with a tendency towards deltaic environment. A metamorphic source is suggested by the presence of garnet, epidote and staurolite while a metamorphic/igneous source may be inferred from the presence of tourmaline and zircon. The high chemical index of alteration (93% average) as well as the low ratio of K_2O/Al_2O_3 (0.03 average) indicate sedimentary recycling and intensive source area weathering. Based on the log (K_2O/Na_2O) discrimination diagram, passive margin tectonic setting may be assigned to Ajali and Owelli Formations. Discrimination function diagram shows a quartzose sedimentary provenance for sediments of Owelli and Ajali Formations. These sediments have been highly reworked from original igneous and metamorphic sources, probably Abakiliki uplift, Oban massif and/or Obudu basement rocks in the southeast.

Hydrocarbon prospect is the probability or success of finding hydrocarbon as oil and gas pools or fields. The prerequisites for the accumulation of oil and gas are good quality source rocks, good quality reservoir and seal lithologies, favourable regional migration pathways as well as trapping mechanisms [11]. The aforementioned requirements are satisfied by Anambra Basin. The maturity of the source rock is also of great importance for the accumulation of oil and gas. From results of analyses carried out on samples of Ajali and Owelli sandstones, we can conclude that the sandstones can serve as fair to poor reservoirs for the petroleum formed in the Nkporo and Mamu Formations, but deeper sections of the sandstones which can be analyzed from core samples will give greater details about the reservoir quality of the sandstones. Shales of the overlying Imo and Nsukka formations can act as regional seal for hydrocarbons that may have been formed and migrated into reservoirs in this part of the basin [11]. Abrupt facies changes in the Anambra Basin can provide stratigraphic traps while local Cenozoic tectonics may have led to the formation of structural traps for hydrocarbon accumulations [11].

3.1. Granulometric Studies

The grain size distribution values of the sandstones plotted on histograms exclusively showed a unimodal pattern, that is, one sediment class dominates. The three types of sediment transport processes (suspension, saltation and surface creep or traction) are reflected on the plots of cumulative weight percent against grain size using a probability scale. The pattern of such plots can serve as a pointer of the depositional environments [14]; [7]. Percentile and quartile values obtained from the cumulative frequency curves were used to generate the grain size parameters with the qualitative interpretation of the sandstones (Table 1). The grain size parameters include graphic mean, inclusive graphic standard deviation (sorting), inclusive graphic skewness and graphic kurtosis. The graphic mean size ranges from 0.94 to 1.01 (coarse to medium grained) with an average of 0.98 (coarse grained) for the Owelli sands. For the Ajali sands, the graphic mean size ranges from 1.50 to 1.93 with an average of 1.63 (medium grained). This implies that the sandstones of the Ajali and Owelli Formations were deposited under a moderately high-energy condition, most likely in a fluvial environment as advocated by [7].

The sorting of the Owelli sandstones ranges from 1.00Φ to 1.20Φ with an average of 1.13Φ which implies that the sandstones are poorly sorted [5]. For the Ajali sandstones, the sorting ranges from 0.89Φ to 0.99Φ with an average of 0.95Φ which implies moderately sorted sandstones. This suggests that the sandstones were deposited under variable current velocities and turbulence, which led to the deposition of variable sand-sized sediments [2].

The Owelli sands have skewness of 0.54 to 0.64 with an average of 0.6 (very fine skewed). The Ajali sands have a skewness of -0.16 to 0.24 (coarse to fine skewed) with an average of -0.03 (near symmetrical).

The kurtosis of the Owelli sands is 1.09 to 1.13 (mesokurtic to leptokurtic) with an average of 1.11 which represents mesokurtic sandstones. The Ajali sands have kurtosis of 0.87 to 1.47 (platykurtic to leptokurtic) with an average of 1.07 (mesokurtic).

Scatter plots of inclusive graphic skewness against sorting and mean grain size against sorting, have been used to distinguish between beach and river sands. Figure 7 and Figure 8 shows that the sandstones of the Ajali and Owelli Formation are river sands that have been deposited in a low energy regime.

Table 1. Statistical parameters of grain size analysis

Sample	Formation	Percentiles							Graphic Mean (M_G)	Skewness (σ_I)	Sorting (S_{KI})	Kurtosis (K_G)	Description
		Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95					
OW18	Owelli	-0.39	0.14	0.24	0.48	1.74	2.42	3.74	1.01	0.64	1.20	1.13	Strongly fine-skewed, poorly sorted, leptokurtic, medium sand
OW19	Owelli	-0.24	0.16	0.28	0.50	1.62	2.17	3.35	0.94	0.62	1.00	1.10	Strongly fine-skewed, moderately sorted, mesokurtic, coarse sand
OW20	Owelli	-0.49	0.13	0.26	0.55	1.72	2.28	3.40	0.99	0.54	1.13	1.09	Strongly fine-skewed, poorly sorted, mesokurtic, coarse sand
AJ21	Ajali	0.35	1.05	1.35	1.95	2.55	2.80	3.75	1.93	0.02	0.95	1.16	Near symmetrical, moderately sorted, leptokurtic, medium sand
AJ22	Ajali	0.20	0.70	0.95	1.40	1.90	2.40	3.60	1.50	0.24	0.94	1.47	Fine skewed, moderately sorted, leptokurtic, medium sand
AJ23	Ajali	0.19	0.58	0.87	1.68	2.19	2.43	3.00	1.56	-0.12	0.89	0.87	Coarse-skewed, moderately sorted, platykurtic, medium sand
AJ24	Ajali	0.13	0.50	0.87	1.72	2.19	2.45	3.09	1.56	-0.16	0.94	0.92	Coarse-skewed, moderately sorted, mesokurtic medium sand
AJ25	Ajali	0.17	0.46	0.86	1.77	2.27	2.51	3.44	1.58	-0.13	0.99	0.95	Coarse-skewed, moderately sorted, mesokurtic, medium sand

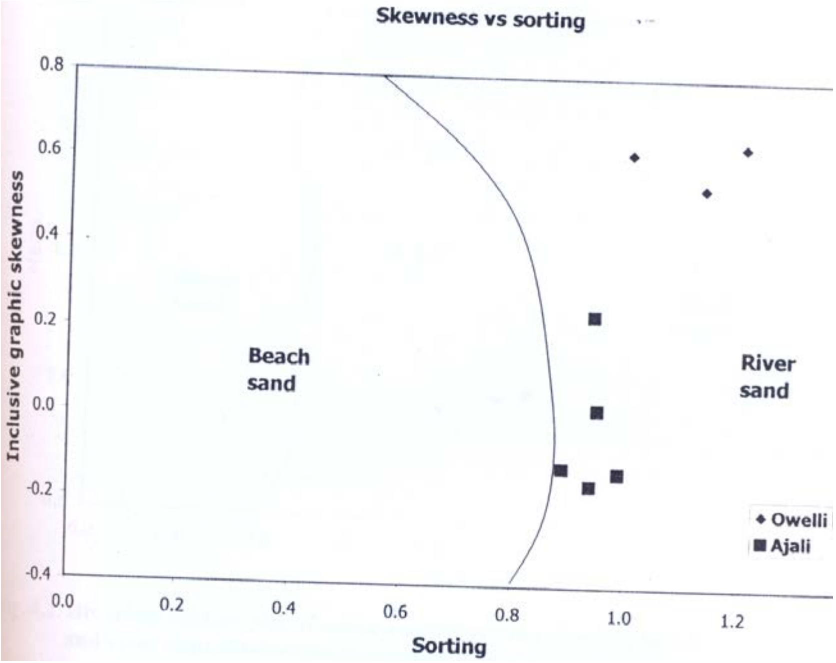

Figure 7. Bivariate Scatter Plot of Skewness against Sorting showing Beach and River Depositional Environment of Sands (after Friedman, 1967)

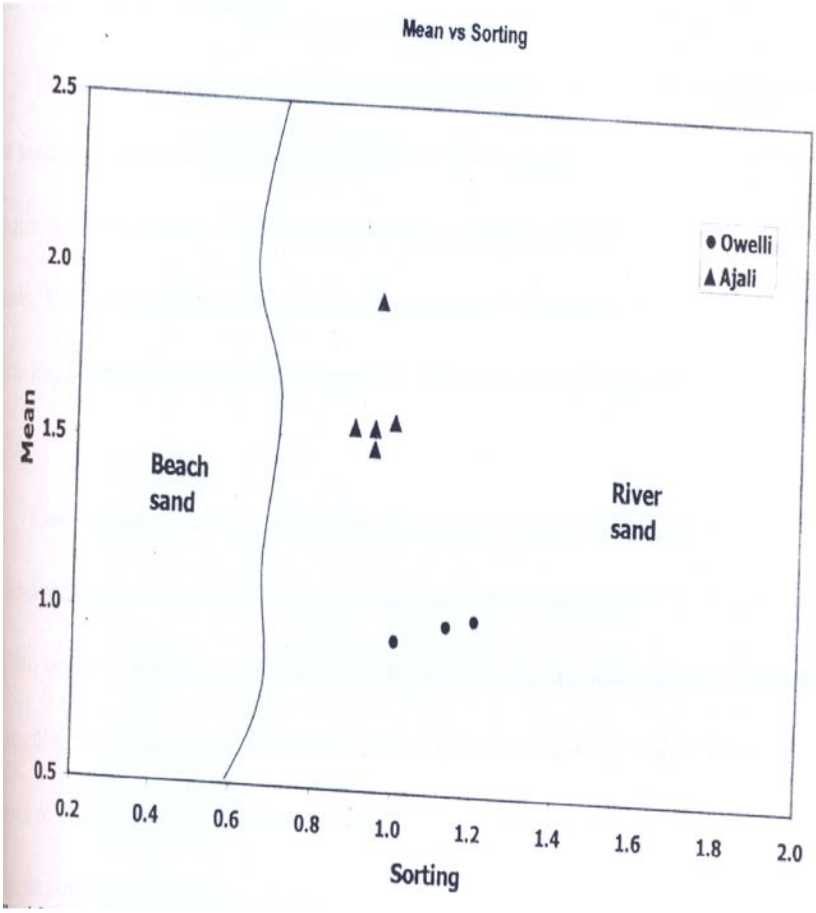

Figure 8. Bivariate Scatter Plot of Mean against Sorting showing Beach and River Depositional Environments of Sands (after Friedman, 1967)

3.2. Thin Section Petrography

Petrographic analysis of the sandstones revealed an average composition of 70.3% quartz, 11.7% feldspar, 4.7% rock fragments, 6.0% cement, 3.7% matrix, 2% heavy mineral and 1.7% mica for the Owelli sands. The Ajali sands have an average composition of 71.0% quartz, 12.4% feldspar, 4.8% rock fragments, 5.4% cement, 4.0% matrix, 1.4% heavy mineral and 1.4% matrix (Table 2).

Based on the framework composition of quartz (Q), feldspar (F) and rock fragment (L); a ternary diagram was plotted for the sandstone samples (see Table 2 and Figure 9). Involving [4] ternary diagram classification for sandstones, the sandstones samples in the study area are subarkosic. Subarkosic sandstones are mechanically stable. However, in terms of chemical stability, subarkosic sandstones are less stable than quartz arenites but more stable than arkosic sandstones (Figure 9).

Table 2. The percentage distribution of minerals in the sandstones of the study area

Sample	MinMineralogical composition (%)						
	Quartz	Feldspar	Rock Fragment	Cement	Matrix	Heavy Minerals	Mica
OW18	72	12	5	7	2	1	1
OW19	68	12	6	6	4	2	2
OW20	71	11	3	5	5	3	2
AJ21	70	14	3	6	5	1	1
AJ22	74	12	6	4	2	1	1
AJ23	72	9	7	5	6	2	1
AJ24	69	14	5	5	3	2	2
AJ25	70	13	3	7	4	1	2

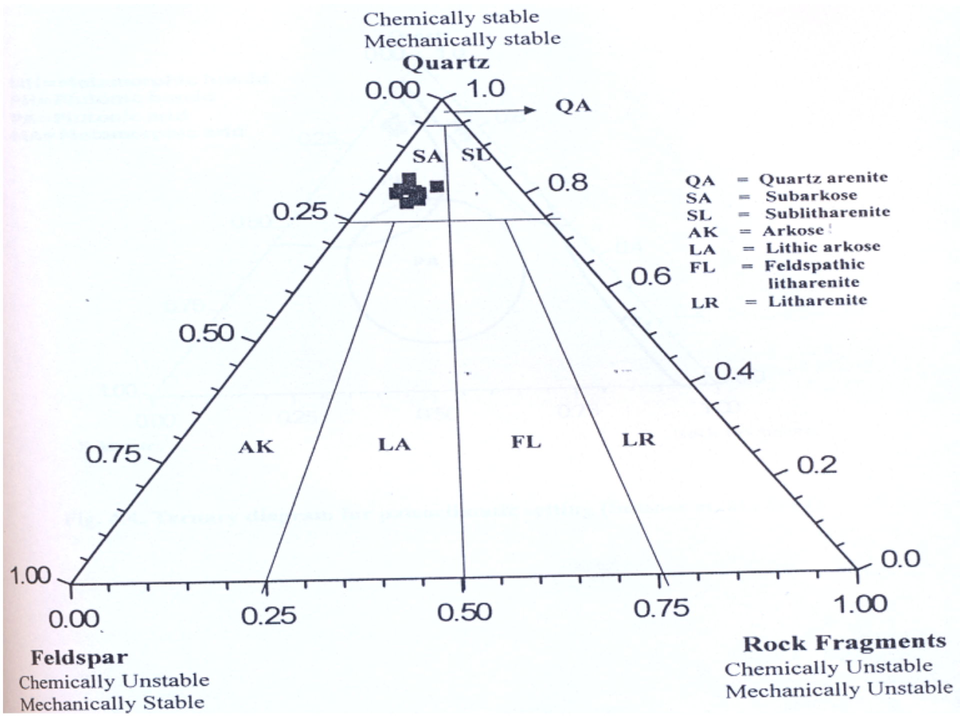

Figure 9. Ternary Diagram of Framework Compositions of the Sandstones (after Folk, 1980 and Hayes, 1979)

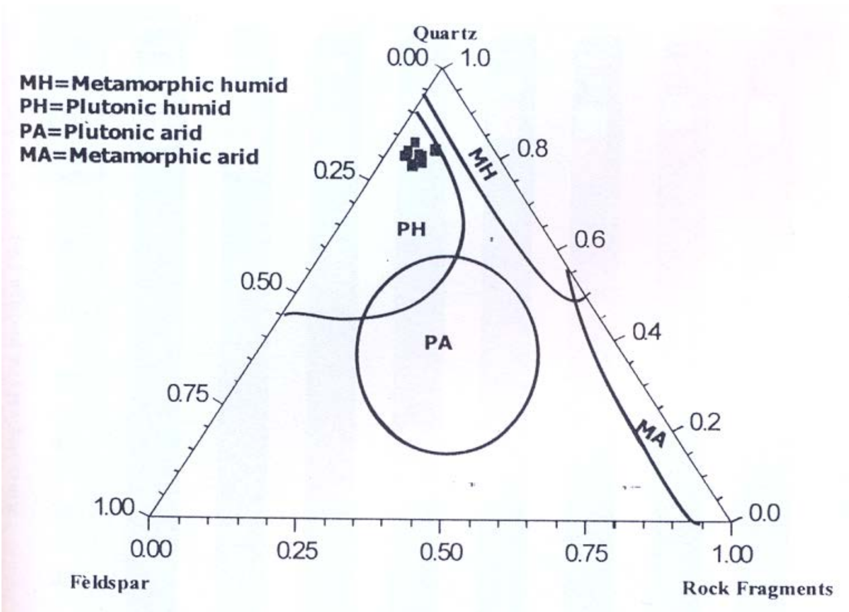

Figure 10. Ternary Diagram for Paleoclimatic Setting (Suttner *et. al.*, 1981)

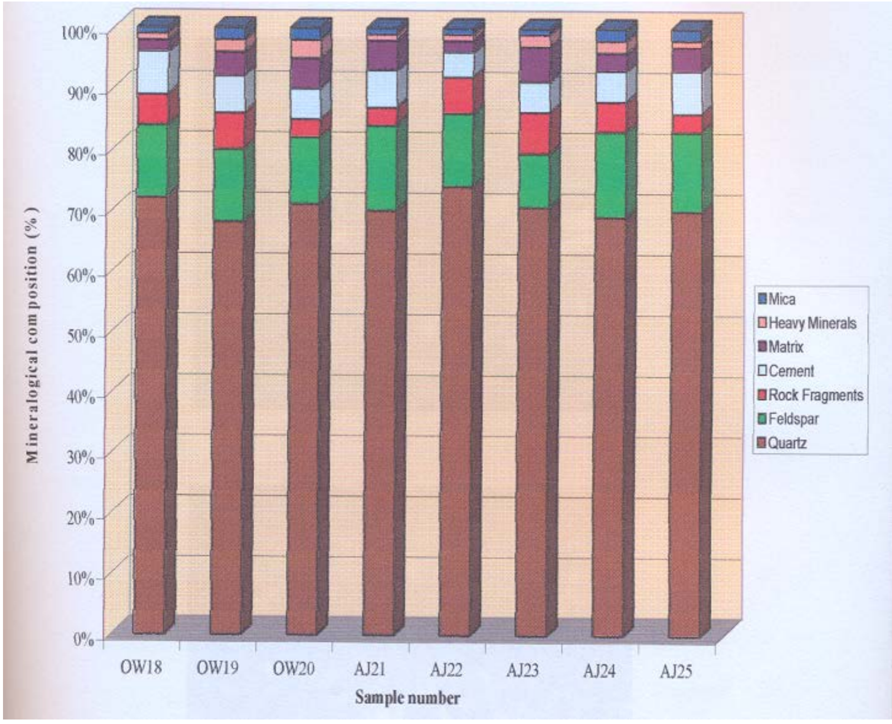

Figure 11. Bar Chart showing the Mineralogical Compositions of the Sandstones in the Study Area

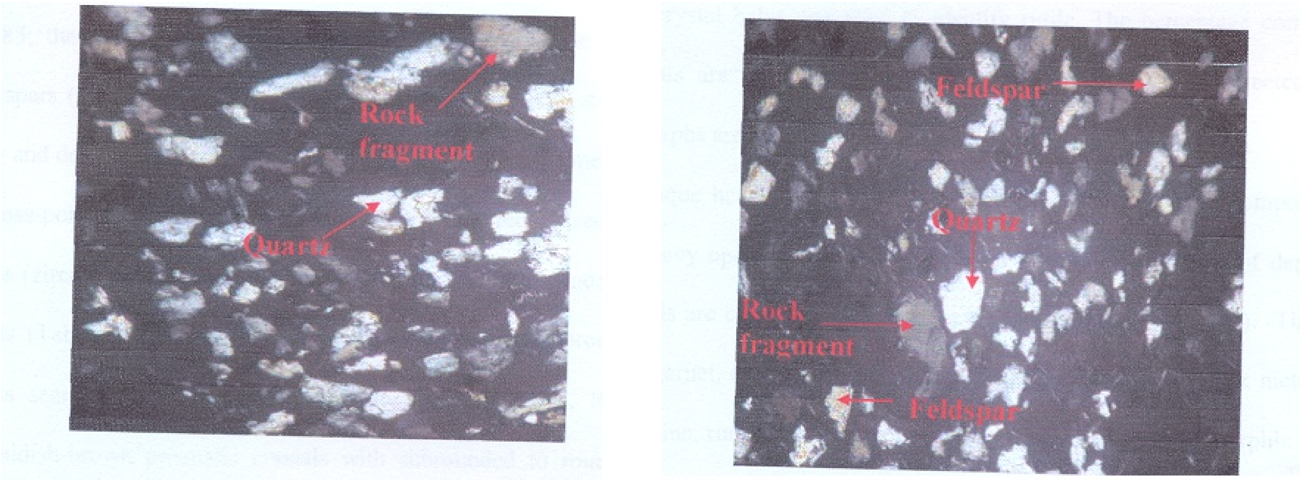

Figure 12. Selected thin Section Photomicrograph of Owelli Sandstone (left) and Ajali Sandstone (right)

The ternary plots as proposed by [13] reveals a plutonic humid paleoclimatic condition for the depositional environment of the sandstones (Figure 10). This can be deduced from the abundance of quartz which was left behind after the weathering of most of the feldspars as a result of humidity.

The sandstone grains are subangular to subrounded, which suggests relatively long distance of transportation. The cement may be iron oxide, fine quartz or silica overgrowth. Selected thin section photomicrographs of the sandstones are shown in Figure 12, while the percentage mineral compositions are presented as a bar chart in Figure 11.

3.3. Heavy Mineral Studies

Heavy minerals are accessory minerals in sediments, with specific gravity greater than 2.85; the specific gravity of bromoform used to separate them from lighter quartz and feldspars [10]. Heavy minerals are useful indicators of provenance, paleogeography and depositional processes operating at the time of sediment deposition. Under cross-polarized light, the heavy mineral species recognized include the non-opaque minerals (zircon, tourmaline, rutile, staurolite, garnet, hornblende, epidote) and the opaque minerals (Table 3). Zircon grains were colourless and subrounded to rounded. Tourmaline was seen as prismatic pale yellow to greenish grains. Rutile occurred as yellowish to reddish-brown prismatic crystals with subrounded to rounded terminations. Rod-shaped crystal habit was used to identify rutile. The percentage compositions of the heavy minerals are presented in a bar chart in Figure 11 and selected heavy mineral photomicrographs are shown in Figure 12. The opaque heavy mineral species exceeded the non-opaque components. The large amount of heavy opaque minerals suggests an aerated environment of deposition. Detrital heavy minerals are characteristic of source rock type according to [12]. The heavy mineral assemblages such as garnet, epidote and staurolite are suggestive of a high rank metamorphic source while tourmaline, rutile and zircon occur in both igneous and metamorphic rocks [7]. Heavy mineral suites may also be used as an index of maturity using the ZTR index. The calculated ZTR index for the sandstones ranges from 63.64 to 71.43 with an average of 68.68 for Owelli Formation; and 58.62 to 70.97 (64.54 average) for Ajali Formation. The implication is that the sandstones of the Ajali and Owelli Formations are mature [8].

3.4. Inorganic Geochemistry

3.4.1. Major and Trace Element Distribution

The percentage composition of major oxides in the sediments of the study area is presented in Table 3 and Figure 13. The average values for the formations are also shown in Table 4. SiO_2 ranges from 83.50% to 86.10% for the sandstones (average 84.48% and 84.66% for Owelli and Ajali Formations). The concentration of Al_2O_3 ranges from 10.63% to 14.56% for the sandstones (13.21% and 12.03% average for Owelli and Ajali Formations). The value of the total iron (Fe_2O_3) ranges from 1.31% to 2.55% for the sandstones (1.56% and 2.19% average for Owelli and Ajali Formations). MgO ranges from 0.01% to 0.77% in the sandstones (0.08% and 0.17% average for Owelli and Ajali Formations).

The value of CaO ranges from 0.02% to 1.08% in the sandstones (0.44% and 0.29% average for Owelli and Ajali Formations). Na_2O ranges from 0.10% to 0.33% in the sandstones (0.19% and 0.18% average in the Owelli and Ajali Formations). The value of K_2O ranges from 0.32% to 0.58% in the sandstones (0.44% and 0.41 average for Owelli and Ajali Formations).

Table 3. Result of Heavy Mineral Studies (Point Count)

S/N	Sample	Opaque	Zircon	Tourmaline	Rutile	Staurolite	Garnet	Hornblende	Epidote	Non-Opaque	ZTR Index
1	OW18	32	5	8	7	4	1	1	2	28	71.43
2	OW19	38	4	4	6	3	2	2	1	22	63.64
3	OW20	26	7	6	9	6	1	1	1	31	70.97
4	AJ21	32	9	5	4	8	1	2	1	30	60.00
5	AJ22	35	8	3	6	7	2	1	1	28	60.71
6	AJ23	30	7	6	8	5	1	-	2	29	72.41
7	AJ24	24	6	5	6	8	1	1	2	29	58.62
8	AJ25	28	8	7	7	7	-	1	1	31	70.97

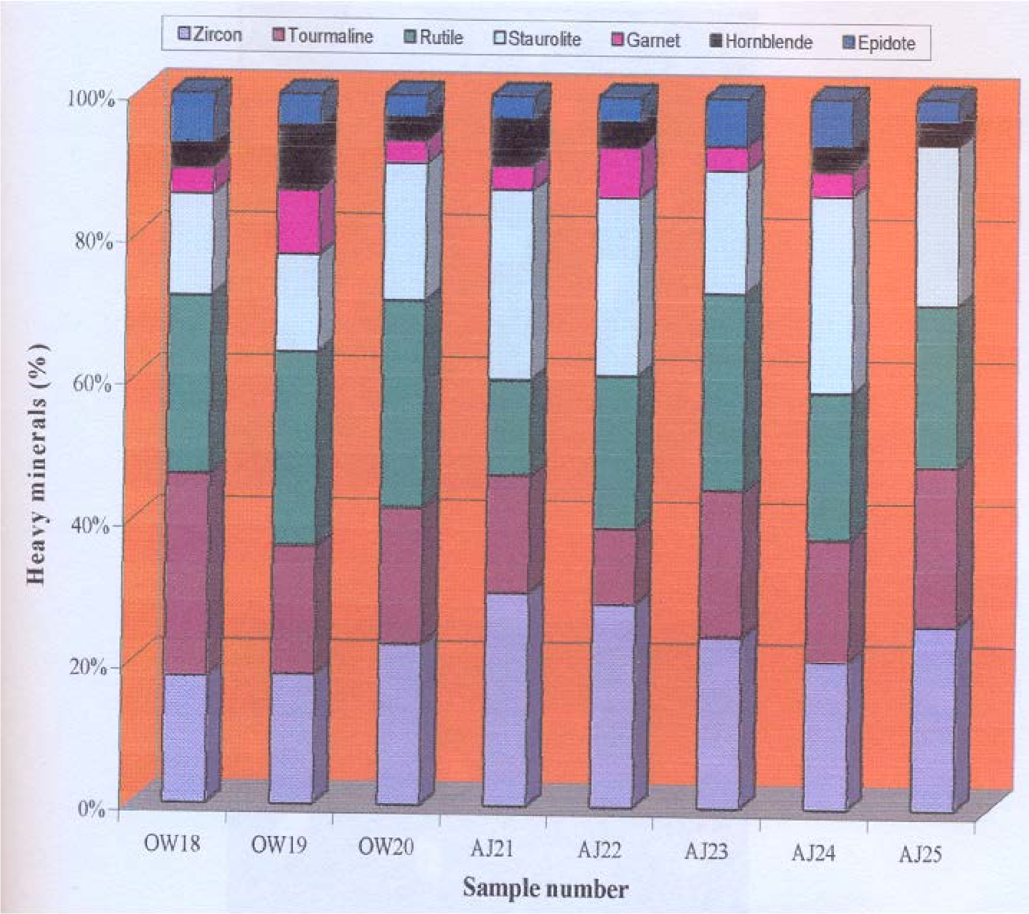

Figure 13. Percentage Distribution of the Heavy minerals in the Sandstone of the Sample Area

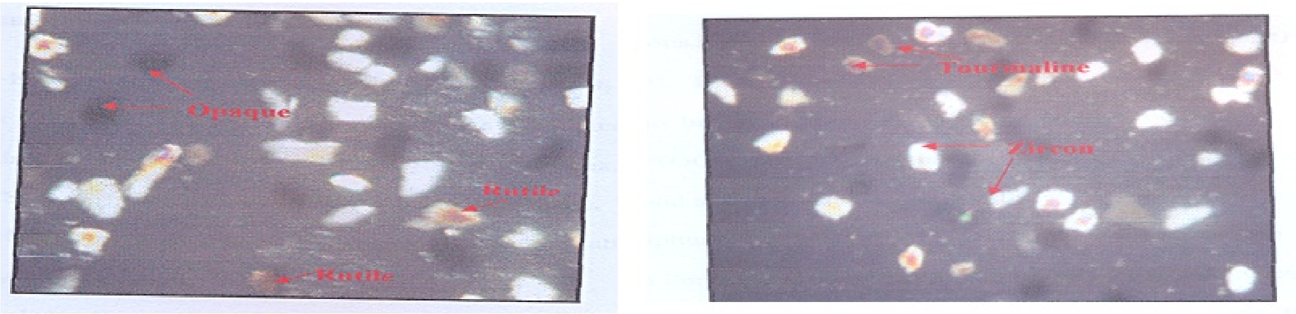

Figure 14. Selected Heavy Mineral Photomicrograph of Owelli Sandstone (left) and Ajali Sandstone (right)

Table 4. Major Elements Distribution (Wt % Oxide)

S	Sample	Formation	(SiO_2) (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3(T) (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	Total (%)
1	W18	Owelli	83.95	0.48	13.76	1.65	0.09	0.01	0.04	0.33	0.58	100.89
2	W19	Owelli	85.00	0.31	14.56	1.31	0.05	0.09	0.19	0.13	0.32	101.96
3	W20	Owelli	84.50	0.49	11.31	1.71	0.08	0.15	1.08	0.11	0.42	99.85
4	AJ21	Ajali	83.50	0.50	13.04	2.25	0.01	0.02	1.01	0.20	0.52	101.05
5	AJ22	Ajali	84.49	0.31	11.04	1.57	0.11	0.77	0.15	0.12	0.34	98.90
6	AJ23	Ajali	86.10	0.36	10.63	1.46	0.02	0.01	0.02	0.27	0.38	99.25
7	AJ24	Ajali	85.20	0.32	12.48	3.14	0.01	0.02	0.13	0.10	0.32	101.72
8	AJ25	Ajali	84.00	0.30	12.96	2.55	0.12	0.04	0.12	0.20	0.46	100.75
	PAAS		62.40	0.99	18.78	7.18	0.00	2.19	1.29	1.19	3.68	97.70
	UCC		66.00	0.50	15.20	4.50	2.20	-	4.20	3.90	3.40	99.90
Owelli			**84.48**	**0.43**	**13.21**	**1.56**	**0.07**	**0.08**	**0.44**	**0.19**	**0.44**	**100.90**
Average :		**Ajali**	**84.66**	**0.36**	**12.03**	**2.19**	**0.05**	**0.17**	**0.29**	**0.18**	**0.41**	**100.33**

Table 5. Trace Element Concentration (In Ppm)

S/N	Sample	Zn (ppm)	Cu (ppm)	Pb (ppm)	Cr (ppm)	Ni (ppm)	Ba (ppm)
1	OW18	210.45	28.38	12.85	112.22	23.87	672.69
2	OW19	141.25	27.45	12.53	112.10	26.35	516.53
3	OW20	221.63	27.82	12.63	112.77	22.31	660.88
4	AJ21	143.60	26.55	22.55	114.60	24.15	670.35
5	AJ22	210.14	24.73	17.20	133.13	21.30	622.55
6	AJ23	164.12	23.82	19.60	125.17	25.25	511.62
7	AJ24	161.15	20.40	18.45	120.40	26.42	674.38
8	AJ25	185.70	22.51	19.10	122.80	22.86	513.93
PAAS		-	-	-	-	-	-
UCC		71	-	-	35	20	550

The results from the study show that the concentration of SiO_2 and Al_2O_3 is high in most samples compared to Upper continental crust (Taylor and McLennan, 1985) and Post Archean Australian Shale (PAAS). There is reasonable reduction in the amount of Fe_2O_3, MgO, CaO, K_2O and Na_2O (Table 4). It is typical for the geochemical character displayed by the sediment to be directly related to the composition of its framework components and other authigenic minerals resulting from diagenesis. The increased alumina from samples in the study area may have resulted from the breakdown of feldspars during weathering and the accumulation of residual Al-bearing clays. Positive correlation exists between SiO_2 and Al_2O_3. There is however a negative relationship between Al_2O_3 and MgO, implying non-association of these oxides with the primary mineralogy of the sediments. The characteristics of the major oxides are principally a reflection of the source material (its provenance).

3.5. Provenance

The provenance (source area) for the sandstones of the study area was established by using geochemical parameters. The provenance of the sandstones was also inferred by considering grain texture, heavy mineral assemblages and mineralogical compositions. The subangular shape of the quartz grains in the sandstones indicates a short distance of transportation. Sandstones that exhibit subangularity in grain shapes are termed submature. Submature sandstones are created by the removal of the clay matrix by current action. The sand grains are, however, still poorly sorted in these rocks. Submature sandstones are common as river-channel sands, tidal-channel sands, and shallow submarine sands swept by unidirectional currents.

The presence of staurolite, hornblende and polycrystalline quartz grains is a good indicator of an original metamorphic source [8]; [7]. A metamorphic source is also suggested by the presence of garnet, epidote and staurolite while the presence of tourmaline and zircon is suggestive of an igneous source of both similar to the basement complex of Nigeria because there is no way sediments deposited in the Anambra Basin could have been exclusively desired from the metamorphic or igneous rocks. The quartzose sedimentary provenance assigned to the sediments implies sandstones that have been highly reworked from originally igneous and metamorphic sources. Based on the standpoint of paleogeography and regional geology, the sandstones may have been sourced from Abakiliki uplift and partly from the highly weathered surrounding crystalline complexes of rifted Oban massif and the Obudu basement rocks in the southeast [1]; [3] actually stated that the Oban massif is more granitic than was previously thought.

3.6. Depositional Paleoenvironment

The environment of deposition of the Ajali and Owelli Sandstones may be inferred from heavy mineral, thin section and grain size analyses. The large amount of heavy opaque minerals in the sandstones indicates an aerated depositional environment. The abundance of quartz in the sandstones is an indication that the paleoclimatic setting at the time of deposition of the sands was probably humid. This is because most of the feldspar weathered away, leaving behind quartz, which is more chemically and mechanically stable. The ternary plot of framework composition of the sandstones confirms a plutonic humid paleoclimate of the depositional environment of Ajali and Owelli Formation.

The Owelli sandstones are poorly sorted while the sandstones of Ajali Formation are moderately sorted. This is suggestive of sediments deposited in a river environment. The bivariate scatter plots of inclusive graphic skewness against sorting and mean against sorting indicate a fluvial depositional environment for the sandstones of the study area. The plots of cumulative weight percent against grain size on probability scale show a 2-segment pattern (representing suspension and saltation populations) implying a river environment for the Ajali sands. The sample from Owelli Formation and one of the samples from Ajali Formation showed a 3-segment pattern of traction, saltation and suspension populations. This means that both high and low energy conditions dominated during deposition characteristics of a deltaic environment [14].

The planar cross-bedding observed in the sandstones further suggests a fluvial depositional environment for the sandstones. Therefore the Ajali and Owelli sandstones were deposited in a fluvial environment with a stretch into deltaic regime.

4. Conclusion

Generally, the reservoir quality is poor to fair because of the nature of the reservoir sand as the porosity and permeability are controlled by diagenesis, grain sizes, sorting, grain contacts and grain shapes. Inversely, grain and cement dissolution, and interconnecting fractures associated with the area as observed in thin section studies and outcrop scales respectively increased the reservoir quality.

This study have shown that Ajali and Owelli sandstones, can serve as good reservoirs for the petroleum formed in the Nkporo and Mamu Formations. Shales of the overlying Imo and Nsukka formations can act as regional seal for hydrocarbons that may have been formed and migrated into reservoirs in this part of the basin. Abrupt facies changes in the Anambra Basin can provide stratigraphic traps while local Cenozoic tectonics may have led to the formation of structural traps for hydrocarbon accumulations.

Acknowledgements

Authors are extremely grateful to Prof. W.O. Emofurieta and Mr. V.B. Bello for their input in this work.

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