Grain Size and Petrographic Studies of Turonian Sandstones in Orimedu-1 and Ise-2 Wells, Dahomey Basin Southwestern Nigeria

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ABSTRACT

Turonian to Coniacian (TC) sandstone from two exploratory wells located in the eastern part of Dahomey Basin, Southwestern Nigeria, were subjected to grain size and petrographic studies to investigate their provenance, paleoenvironments and preliminary reservoir properties. The textural characteristics of the TC sandstones were inferred from the statistical variables mean, standard deviation (sorting), skewness and kurtosis with values of 0.10 – 0.79 (average 0.45phi), 0.72 – 1.00 (average 0.87phi), -0.76 – 0.46 (average 0.13phi) and 0.69 – 2.17 (average 1.07phi) respectively. Quartz, feldspar and rock fragment ranges from 90 - 96 % (average of 93.3%), 1 -3 % (average 1.6%) and 3 – 8 % (average 5.1%) respectively. While non-opaque heavy minerals which are generally less than the opaque include zircon the most dominant followed by tourmaline, rutile, garnet, sillimanite and apatite the least.

The sandstones are coarse grained, moderately sorted, sub-angular to sub-rounded indicating a considerable long-distance transportation history from the source. Moderate sorting and positive skewness point to medium to low energy environment characterized by fairly consistent water current typical of fluvial and shallow marine environments. Most statistical variables favoured dominance of fluvial origin for all the sandstones. Further integration of mineralogy and Zircon-Tourmaline-Rutile (ZTR) index (62 % – 74 %) suggest that the TC sandstones are sublitharenite to quartz-arenites and as well sub mature to mature mineralogically and texturally. They are derived from the continental craton interior with highest supply from humid metamorphic origin followed by acid igneous and reworked sediments.

The preliminary and empirical porosity and permeability inferred from grain size distribution and mineralogy shows that Turonian-Coniacian sandstones have good potential as a reservoir rocks with obvious textural variation from the two wells suggesting that the properties are not uniformly distributed across the basin.

Keywords: Turonian- Coniacian, Sandstones, Provenance, Paleoenvironments, Reservoir

INTRODUCTION

Petroleum exploration effort in the eastern part of Dahomey Basin Southwestern Nigeria is gradually increasing and improving with the recent commercial oil and gas discovery within the upper Cretaceous petroleum play. The play consists of Pre-Santonian siliciclastic reservoir yet to be fully studied compared with the contiguous well-known Tertiary reservoir of the Niger Delta Basin. Evaluation of the provenance, depositional environments, and diagenetic properties of the Pre-Santonian sandstones will shed more light on their reservoir properties.

The sedimentation of sandstones and other associated lithofacies in the Dahomey Basin began in the Early Cretaceous and was controlled by tectonic evolutions related to subsidence, rifting, and drifting similar to events in other Gulf of Guinea basins including the Seme, Tano, Saltpond, Keta and Ivory Coast Basins (Figure 1) (Brownfield and Charpentier, 2006).

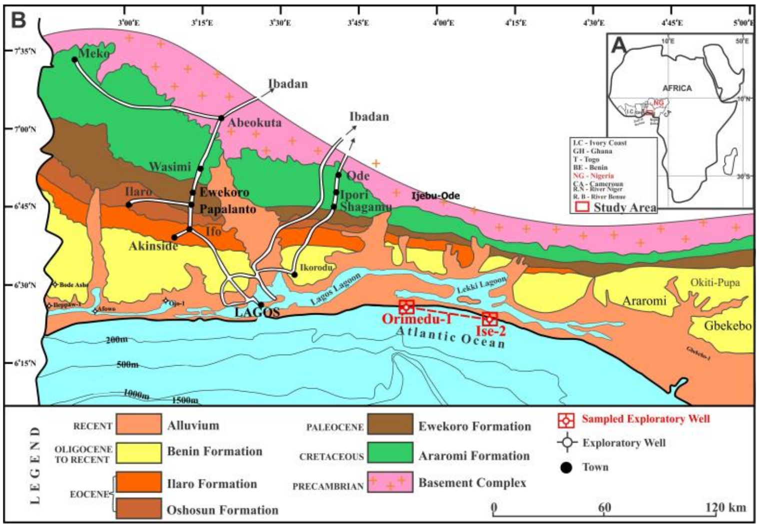

Figure 1: A. Location of Dahomey Basin in the Gulf of Guinea area of West Africa in red box, B. Geological map of Dahomey Basin, southwestern Nigeria showing the location of the Orimedu-1 and Ise-2 exploratory wells in the Ocean margin (Modified after Adeoye et al., 2020).

The basin has other economically viable mineral resources such as limestones for cements production, clay deposits for pottery and hydrothermal energy. Limestone deposit being the most developed mineral resource serves as raw material in the production of cement. Despite the large bitumen deposit in the basin, commercial discovery of oil and gas is very recent and currently under developments and has opened windows for more research opportunities. The Pre-Santonian sandstones is being targeted as the main potential reservoirs for the conventional oil and gas, thus the need for further studies on their petrophysical properties. Therefore, the Cenomanian to Turonian sandstones lithofacies encountered in Orimedu-1 and Ise-2 wells were selected and subjected to granulometric analysis, thin section petrography and heavy mineral study to investigate how provenance, depositional environment and diagenesis impact their reservoir properties.

Geology and Stratigraphy of Dahomey Basin

The breakup of South America and African lithospheric plate in the Late Jurassic to Early Cretaceous is believed to have been controlled by the Romanche, Chain and Charcot transform faults. The tectonic rifting events led to the creation of Dahomey and other West African Rift System (WARS) basins as the period was characterized by uplift, erosion, subsidence and development of series of horst and graben (Figure 2a). This structural feature provides the accommodation space and controlled sedimentation from Cretaceous to Tertiary.

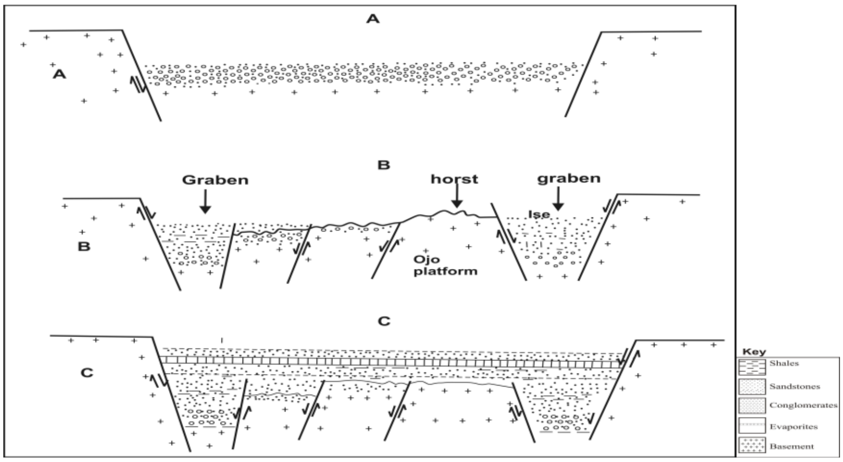

Fig 2**:** Stages of structural development and accommodation space for sedimentation from Cretaceous (A-B) to Tertiary (C) in the Dahomey Basin.

Some of the deposited lithofacies are evaporites, siliciclastic and carbonate of continental and marine source piled up with varied thicknesses across the basin (Omatsola and Adegoke, 1981 and Onuoha and Ofoegbu, 1988). The opening of South American and African plate due to intense and continuous rift activities in the mid Cretaceous connected the South and North Atlantic Oceans. This connection resulted in full marine transgression in the Gulf of

Guinea area with deposition of marine sequences conformably above the initial and older continental sediment. The pre-rift continental sediments and syn-rift marine sequences of Neocomian to Albian are classified as Ise Formation, succeeded by the Cenomanian-Turonian transgressive marine shales, followed by Turonian to Santonian regressive sandstones of Afowo Formation. This was then overlaid by Araromi shales in the Campanian to Maastrichtian before the Neogene and Paleogene carbonate, shales and sand sequences (Figure 2c), Adegoke (1969), Ako et al. (1980), Omatsola and Adegoke (1981), Adediran and Adegoke (1987), Brownfield and Charpentier (2006). Onuoha and Ofoegbu (1988).

Sedimentary Facies

Lithofacies including shales, sandstones, claystones and thin limestone bed from Orimedu-1 and Ise-2 wells located at the coastline of southwestern Nigeria, Dahomey Basin, (Figure 1) were sampled and logged. The biostratigraphy zonation of the two wells in Adekeye et al. 2019 was used as guide for sampling Turonian to Coniacian (TC) sandstones for this study (Figure 3). The Turonian – Coniacian sandstones occurred in three stratigraphic intervals of the Orimedu-1 well as 14 m thick Early Turonian sandstones (1436 – 1450 m), 134m thick Late Turonian sand (1207 – 1341 m) and 438 m thick Middle Coniacian sandstones (744 – 1182 m) while in Ise-2 well within the Early Coniacian (2900 – 3251 m) and Late Coniacian (2400 – 2780 m) stratigraphic interval with 351 m and 380 m thicknesses respectively.

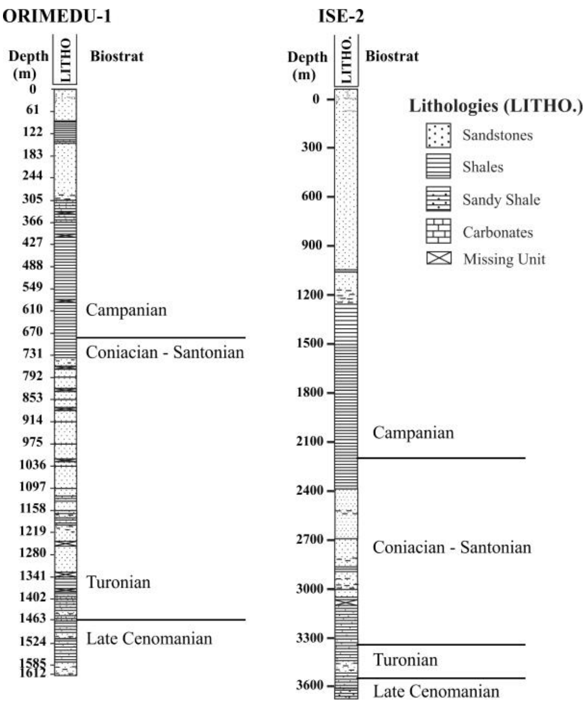

Figure 3: Litho/biostratigraphic sections of Orimedu-1 and Ise-2 well showing the Turonian to Coniacian sandstones.

Orimedu-1 Well

This exploratory well located on the coastline east of the city of Lagos penetrated total depth of 1612m (TD) (Figure 1). The encountered lithofacies consist essentially of shales and sandstones. The base of the well consists of 244m thick grey silty and sandy shale overlained by a medium to coarse grained sandstone at the middle, succeeded by a grey shale and capped by alternating shale-sandstone heterolithic facies.

Sandstones Lithofacies

27m shaly sandstone from the base of the well and succeeded by the Turonian-Coniacian 610m medium – coarse grain TC sandstone. The sandstones are generally loose, coarse grained and moderately sorted, sub-angular to sub rounded capped by about 365m thick grey shale.

Ise-2 Well

Ise-2 well located along the coastline, 70 km east of Orimedu-1 penetrated a total depth of about 3600m. Well report indicates that the Ise-2 penetrated the Cambrian to Lower Paleozoic crystalline basement. The well consists of shales, sandstones and thinly bedded limestones as represented in the composite section (Figure 3). The clastic have cyclic pattern of successions similar to that of Orimedu-1. The base consists of a sandy grey shale overlain by shaly sandstone, followed coarse grained sandstones later succeeded by a massive laminated grey shale and capped by fossiliferous medium to coarse grain sandstones.

Sandstones Lithofacies

The 610 m thick shaly sandstones occur in the lower half of the well above the sandy shale unit. This lithology is loose, medium to coarse grained, and moderately sorted. They are also subangular to sub-rounded.

METHODOLOGY

Granulometric Analysis

Seventeen selected samples of unconsolidated TC sandstones were subjected to mechanical dry sieving. This was done to assess the statistical data on grain distributions. The sizes of sieve used were 2.36, 1.6, 1.18, 0.5, 0.30, 0.25, 0.112, 0.063 and <0.063 mm and were arranged vertically in the order of decreasing mesh size of the sieves. 100 g of loose and dry sandstone samples were measured with the use of electronic weighing balance and carefully poured into the topmost sieves which have been set on the mechanical sieving machine. The sieving machine was switched on for at least five minutes to sieve each sample into separate grain sizes. The grains retained in each sieve were weighed, labelled and recorded. These data were further subjected to statistical calculation before plotting for necessary interpretations.

Thin Section Analysis

Twenty loose TC sandstones samples were impregnated using epoxy glue for 24hrs and allowed to core. Each sample was cut to fit on a glass slide then smoothened with 100grits carborundum in slurry until no more trace of pits and impression were noticeable. They were placed on a hot plate at about 95^{o}C to dry up. Equal proportion of araldite and hardner 93^{o}F were mixed in a small dish that was placed on the hot plate. They were then mounted on the glass slide and left for another thirty (30) minutes on the hot plate after which they were removed, cooled, and grounded to about 0.3 mm thin layer on the glass slide with occasional observations under the petrological microscope. They were further covered with glass slides using Canada balsam as adhesive. The slides were labelled accordingly and made ready for detailed study under a petrological microscope.

Heavy Mineral Analysis

The heavy minerals in sandstones are defined by a lower limit of specific gravity, 2.85, which corresponds to that of a common separating fluid-bromoform. Twenty selected samples were separated by the specific gravity method, where 10g of each sample was poured into the bromoform in a separating funnel, stirred vigorously and allowed to settle gravitationally. The settled minerals were then flushed out through the separating funnel tap into another funnel lined with filter paper. The resulting filtrates (heavy minerals) were then treated with dil. HCl and acetone (CH_3COOH) to remove carbonate clay or iron oxide coating. After being dried, the heavy minerals were mounted on micro glass slides with Canada balsam. The slides were later examined under a petrogrpahic microscope using transmitted light to observe the minerals. Each mineral type was identified based on optical characteristics such as colour, pleochroism, absorption, relief, extinction and birefringence, size, crystal form, elongation, inclusions, cleavage and twinning. Grain counting were carried out on microscopic slide and relative abundance of each were calculated to give number percentage, since the precision of heavy mineral is largely a function of the number of grains counted.

RESULTS

Grain Size Distribution

The grain size analysis results of the sandstones were used to estimate their textural features such as the mean, standard deviation (sorting), skewness and kurtosis (Table 1). Their mean and sorting generally ranges from 0.10 – 0.79 (phi) with average of 0.43 (phi), and 0.72 – 1.00 (Phi) averaging 0.85 (Phi) respectively (Table 1).

Table 1: Results of the textural parameters and interpretations of Late Cretaceous sandstones in the Orimedu-1 and Ise-2 wells of the southern traverse.

	Values (Phi)				Interpretation			
Depth	**Mean**	**Sorting**	**Skewness**	**Kurtosis**	**Mean**	**Sorting**	**Skewness**	**Kurtosis**
ORIMEDU-1 WELL								
ORI-823	0.36	0.72	0.02	1.40	Coarse Sand	Moderately Sorted	Near Symmetrical	Leptokurtic
ORI-951	0.19	0.82	-0.76	1.77	Coarse Sand	Moderately Sorted	Strongly Negatively Skewed	Very Leptokurtic
ORI-1006	0.79	1.06	-0.04	1.64	Coarse Sand	Poorly Sorted	Near Symmetrical	Very Leptokurtic
ORI-1073	0.72	0.94	0.28	0.89	Coarse Sand	Moderately Sorted	Positive Skewed	Platykurtic
ORI-1158	0.21	0.83	0.16	0.93	Coarse Sand	Moderately Sorted	Positive Skewed	Mesokurtic
ORI-1250	0.73	1.00	0.18	1.01	Coarse Sand	Moderately Sorted	Positive Skewed	Mesokurtic
ORI-1280	0.20	0.84	0.16	0.80	Coarse Sand	Moderately Sorted	Positive Skewed	Platykurtic
ORI-1311	0.73	1.00	0.18	1.01	Coarse Sand	Moderately Sorted	Positive Skewed	Mesokurtic
OR-1335	0.21	0.83	0.15	2.17	Coarse Sand	Moderately Sorted	Positive Skewed	Very Leptokurtic
ISE-2 WELL								
2350-2490	0.30	0.78	0.17	0.82	Coarse Sand	Moderately Sorted	Very Positively Skewed	Platykurtic
2500-2550	0.59	0.77	0.20	0.62	Coarse Sand	Moderately Sorted	Very Positively Skewed	Very Platykurtic
2600-2670	0.54	0.92	0.46	0.89	Coarse Sand	Moderately Sorted	Very Positively Skewed	Platykurtic
2780-2800	0.51	0.95	0.13	0.85	Coarse Sand	Moderately Sorted	Very Positively Skewed	Platykurtic
2830-2890	0.21	0.83	0.18	0.92	Coarse Sand	Moderately Sorted	Very Positively Skewed	Mesokurtic
2910-2950	0.72	0.93	0.23	0.90	Coarse Sand	Moderately Sorted	Very Positively Skewed	Platykurtic
2950-3030	0.10	0.79	0.31	0.87	Coarse Sand	Moderately Sorted	Very Positively Skewed	Platykurtic
3410-3500	0.48	0.79	0.14	0.69	Coarse Sand	Moderately Sorted	Very Positively Skewed	Platykurtic

Thin Section Petrography

Turonian to Coniacian sandstones of Orimedu-1 and Ise-2 are unconsolidated, coarse grained, moderately sorted and sub-angular to sub-rounded. The mineral identified were essentially grouped into quartz, feldspar and rock fragments or lithoclast. Ternary QFL-plot after McBride (1963) was used to classify the samples. All the counted monocrystalline and polycrystalline quartz and chert grains are combined as “quartz” (Q). K-feldspar, microcline and plagioclase are summed up as feldspar component (F) and the lithoclast (L) component include all rock fragments. Most of the quartz grains exhibit strained to undulose extinction with sub-angular, sub-rounded, to rounded shapes (Figure 4 and 5). The quartz grains possess both polycrystalline and monocrystalline grain structure. Polycrystalline grains are more abundant than monocrystalline in all the samples with average proportion ranging from 63% to 37% in the two locations. Quartz mineral grains are predominant representing 90 to 94% (mean 92.3%) in Orimedu-1 and 92 – 96% (mean 95%) in Ise-2, feldspar is less than 2% while the lithoclasts or rock fragments were in the range of 4 to 6% (Table 2).

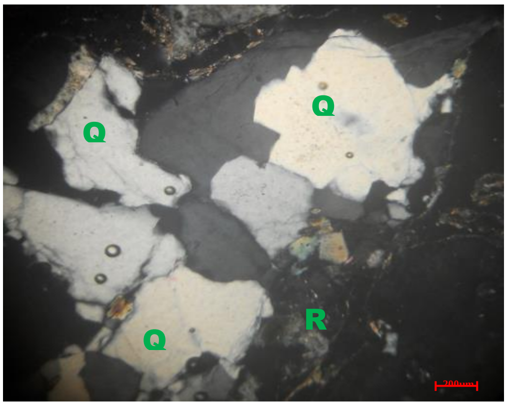

Figure 4: Thin section photomicrograph of representative samples of sandstones from Orimedu-1 well sub-angular to sub-rounded mineral grains. (Q - Quartz, RF - rock fragments).

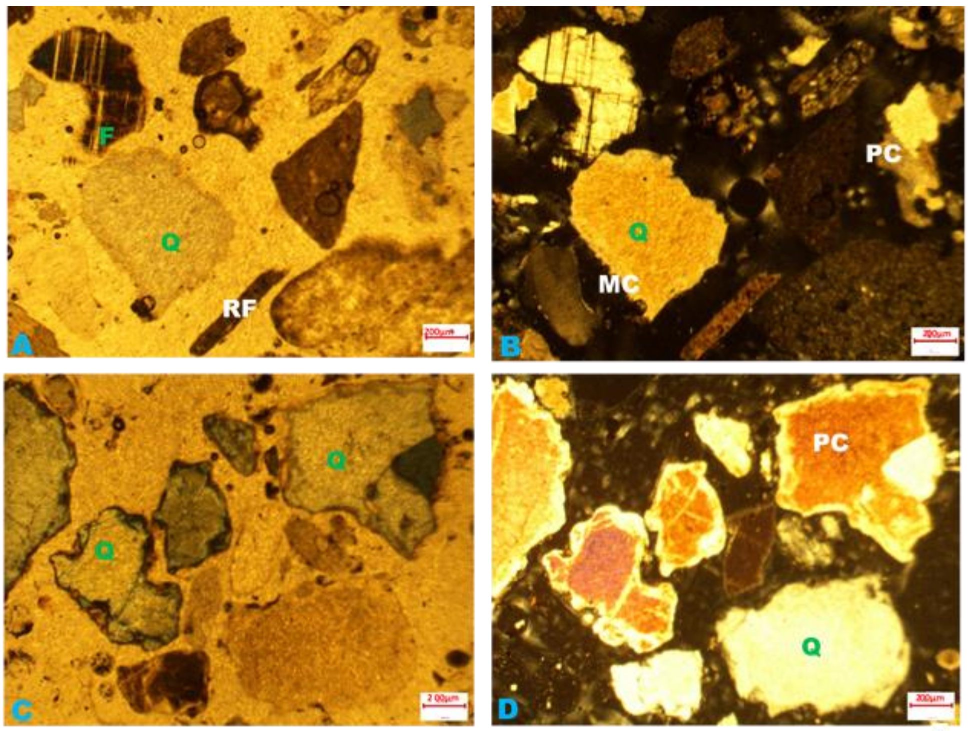

Figure 5: Photomicrograph of a sandstones from Ise-2 well (A & C are plane polarized light while B, & D are Cross polar light) showing polycrystalline quartz (PC), monocrystalline quartz (MC), quartz (Q), Feldspar (F-microcline) and rock fragments (RF) along with the subangular to sub-rounded grain shape.

Table 2: Average modal results of the abundance of framework component of Turonian sandstones in Orimedu-1 and Ise-2 wells.

	QFL (%)		
Sample No	**Quartz (Q)**	**Feldspar (F)**	**Rock fragment (RF/L)**
Orimedu-1			
ORI-823	92	2	6
ORI-951	93	1	6
ORI-1006	91	2	7
ORI-1073	94	1	5
ORI-1158	93	2	5
ORI-1250	94	1	5
ORI-1280	90	3	7
ORI-1311	93	2	5
ORI-1335	92	2	6
ORI-1512	91	1	8
Ise-2			
ISE-2A	94	2	4
ISE-2B	95	1	4
ISE-2C	92	2	6
ISE-2D	95	1	4
ISE-2E	94	1	5
ISE-2F	95	1	4
ISE-2G	95	2	3
ISE-2H	96	1	3
ISE-2I	94	2	4
ISE-2J	95	2	3

Heavy Mineral

Heavy minerals are useful and reliable indicator of provenance or source of clastic sediments. Both opaque and non-opaque minerals were observed in the samples. The percentage of the opaque mineral is more than that of the non-opaque minerals. Opaque minerals are dark under the petrographic microscope, and they include haematite, limonite and magnetite. Non-opaque minerals identified are Zircon, Tourmaline, Rutile, Garnet, Sillimanite and Apatite (Figure 6). Zircon, Rutile and Tourmaline are ultra-stable heavy minerals that can withstand prolonged abrasion and survive many re-workings (Feo-codecido,1956).

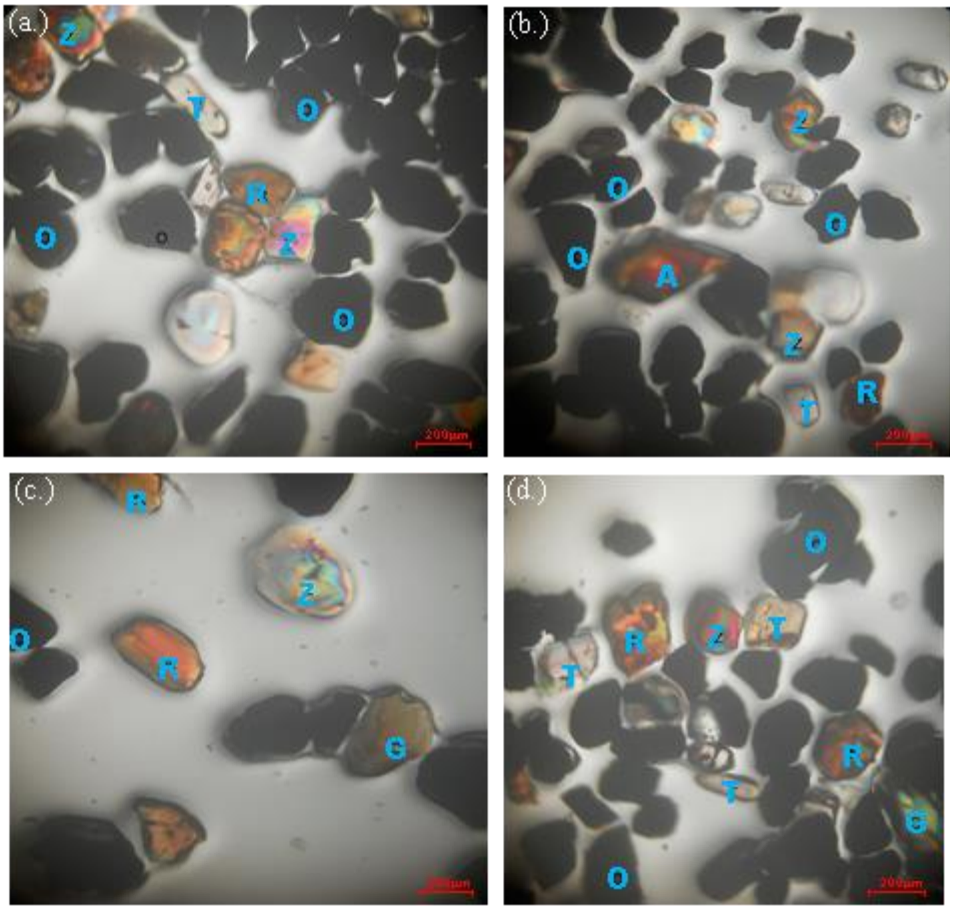

Figure 6: Photomicrograph of heavy minerals in the Turonian sandstones samples of Orimedu-1 and Ise-2 wells. (Z- Zircon, T- Tourmaline, R- Rutile, G- Garnet, A- Apatite, O- Opaque)

Table 3. Heavy mineral analysis of Turonian sandstones from Orimedu-1 and Ise-2 wells

Sample No	Zircon	Rutile	Tourmaline	Sillimanite	Garnet	Apatite	Opaque
Orimedu-1							
ORI-823	5	4	5	2	2	1	18
ORI-951	7	4	5	2	2	2	21
ORI-1006	6	5	4	2	3	3	17
ORI-1073	6	5	6	3	3	2	22
ORI-1158	3	4	4	1	3	2	15
ORI-1250	5	6	4	2	3	2	20
ORI-1280	5	3	6	3	3	2	19
ORI-1311	4	5	6	2	3	1	23
ORI-1335	5	6	7	4	4	3	22
ORI-1512	3	4	6	2	2	2	18
Ise-2							
ISE-2A	7	5	5	2	3	1	20
ISE-2B	6	5	6	3	2	2	19
ISE-2C	6	7	6	3	4	3	22
ISE-2D	5	5	4	2	3	2	21
ISE-2E	5	4	5	3	3	2	17
ISE-2F	5	6	3	2	3	1	15
ISE-2G	6	4	5	2	4	3	22
ISE-2H	7	5	8	3	3	3	20
ISE-2I	6	4	5	4	5	3	16
ISE-2J	6	5	5	2	4	2	23

Calculated Porosity and Permeability

Empirical prediction of petrophysical properties such as porosity and permeability of clastic reservoir (Kozeny, 1927; Carman, 1937; Berg, 1970, Beard and Weyl, 1973; Scherer, 1987; Waples, 2002) were carried out since the needed parameters including texture, stratigraphic age and burial history are available from this study. Scherer 1987 equation (i) and method was employed in estimating the depositional or original porosity ($Ø_o$) and equation (ii) for present-day porosity ($Ø_p$) which is expected to have reduced as a result of compaction and cementation.

$Ø_o = 20.91 + 22.9/S0$ ……………………………………………………………………i

where, S_o is the Trask sorting coefficient based on sorting parameter.

$Ø_p = 18.60 + 4.73 \ln (Q) + 17.37/S0 – 0.0038(Z) – 4.65 \ln (A)$…………………………..……..ii

where, $Ø_p$ is the present-day porosity in percent, Q is the total quartz percentage in the rock, S_o is the Trask sorting coefficient, Z is the maximum burial depth expressed in meters, and A is the age of the rock in millions of years (Sonibare, 2011).

The permeability values calculated using the equation (iii) by Kozeny, 1927 and Carman, 1937 is dependent on rock pore size; and its assumption is that pore spaces are composed of a bundle of identical capillary tubes address as simplified description of natural porous media by Sonibare, 2011. Carman (1939) suggested that constant, c in the equation gave the best experimental results when it equals 2

$$K_{kc} = \frac{cd^2ø^3}{(1-ø)^2}$$ ……………………………………………………………………iii

where, c = constant, d = median grain size i.e. representative grain size (mm), Ø = porosity. Whereas, Berg (1970) derived his equation (iv) for permeability based on sphere packing:

$$K_B = 5.1 \text{ x } 10^{-6} \text{ x } d^2 Ø^{5.1} e^{-1.385}$$ ………………………………………………………iv

where, *d*= median grain size i.e. representative grain size (mm), = porosity. Therefore, Berg model is an equation linking petrological variables- grain size, shape and sorting to permeability. The result outcomes are presented in Table 4 and 5

Table 4: Calculated porosity for Turonian-Coniacian sandstones

Sample No	Quartz %	Sorting	So	Age	Depth (m)	$Ǿ_o$	$Ǿ_p$
ORI-823	92	0.72	1.80	86.3	823	33.6	25.8
ORI-951	93	0.82	1.80	87.0	951	33.6	25.3
ORI-1006	91	1.06	2.35	87.5	1006	30.7	22.7
ORI-1073	94	0.94	1.80	88.0	1073	33.6	24.8
ORI-1158	93	0.83	1.80	89.0	1158	33.6	24.4
ORI-1250	94	1.00	1.80	89.5	1250	33.6	24.1
ORI-1280	90	0.84	1.80	90.0	1280	33.6	23.7
ORI-1311	93	1.00	1.80	91.0	1311	33.6	23.7
OR-1335	92	0.83	1.80	92.0	1335	33.6	23.5
2350-2490	94	0.78	1.80	86.3	2490	33.6	19.5
2500-2550	95	0.77	1.80	87.0	2550	33.6	19.3
2600-2670	92	0.92	1.80	87.5	2670	33.6	18.7

2780-2800	95	0.95	1.80	88.0	2800	33.6	18.3
2830-2890	94	0.83	1.80	88.2	2890	33.6	17.9
2910-2950	95	0.93	1.80	88.5	2950	33.6	17.7
2950-3030	95	0.79	1.80	88.7	3030	33.6	17.4
3410-3500	96	0.79	1.80	89.0	3500	33.6	15.7
					Average Values	33.5	21.3

So= Trask Sorting, Ǿo= Depositionl porosity, Ǿp=Present day porosity

Table 5: Calculated Permeability of Turonian-Coniacian sandstones

Sample No	**Grain Size**	**Sorting**	**Median Size (mm)**	**Ǿo (%)**	**Ǿp (%)**	**K_{ok-c} (mD)**	**K_{pk-c} (mD)**	**K_{oB} (mD)**	**K_{pB} (mD)**
ORI-823	Coarse Sand	MS	1.80	33.63	25.78	41.04	24.34	44.63	11.56
ORI-951	Coarse Sand	MS	1.80	33.63	25.31	43.98	25.16	47.83	11.27
ORI-1006	Coarse Sand	MS	2.35	30.65	22.71	26.61	14.78	19.91	4.28
ORI-1073	Coarse Sand	MS	1.80	33.63	24.84	27.08	14.93	29.44	6.31
ORI-1158	Coarse Sand	MS	1.80	33.63	24.42	62.20	33.17	67.63	13.28
ORI-1250	Coarse Sand	MS	1.80	33.63	24.09	27.08	14.06	29.44	5.40
ORI-1280	Coarse Sand	MS	1.80	33.63	23.75	62.20	31.41	67.63	11.52
ORI-1311	Coarse Sand	MS	1.80	33.63	23.73	31.10	15.68	33.81	5.74
OR-1335	Coarse Sand	MS	1.80	33.63	23.54	62.20	30.87	67.63	11.01
2350-2490	Coarse Sand	MS	1.80	33.63	19.55	50.52	17.45	54.94	3.47
2500-2550	Coarse Sand	MS	1.80	33.63	19.33	54.16	18.31	58.89	3.51
2600-2670	Coarse Sand	MS	1.80	33.63	18.70	35.72	11.32	38.85	1.96
2780-2800	Coarse Sand	MS	1.80	33.63	18.33	38.28	11.67	41.63	1.89
2830-2890	Coarse Sand	MS	1.80	33.63	17.93	58.04	16.94	63.12	2.56
2910-2950	Coarse Sand	MS	1.80	33.63	17.73	27.08	7.74	29.44	1.13
2950-3030	Coarse Sand	MS	1.80	33.63	17.42	82.08	22.66	89.25	3.13
3410-3500	Coarse Sand	MS	1.80	33.63	15.67	41.04	9.23	44.63	0.91
			Average Values	33.46	21.34	45.32	18.81	48.75	5.82

MS-Moderately Sorted, K_{ok-c}, & K_{pk-c} = calculated original and present Kozeny-Carman permeabilities in Darcy (D), K_{oB}, K_{pB} = calculated original and present Berg permeabilities in Darcy (D) respectively for the calculated porosity values.

DISCUSSIONS

Mineralogy: The mineral constituents of Turonian-Coniacian (TC) sandstones from thin section petrography are predominantly quartz with average value of 92.3% and 95%, Microcline and plagioclase feldspar 1.7% and 1.5% and rock fragments 6% and 4% in Ormedu-1 and Ise-2 well respectively. Ternary plot of quartz-feldspar-lithoclast after

(McBride, 1963) shows that TC sandstones in Orimedu-1 are sublitharenite while it is quartz-arenites in Ise-2 (Figure 13), thus reflecting that the sandstones mineralogy and texture range from sub mature to mature.

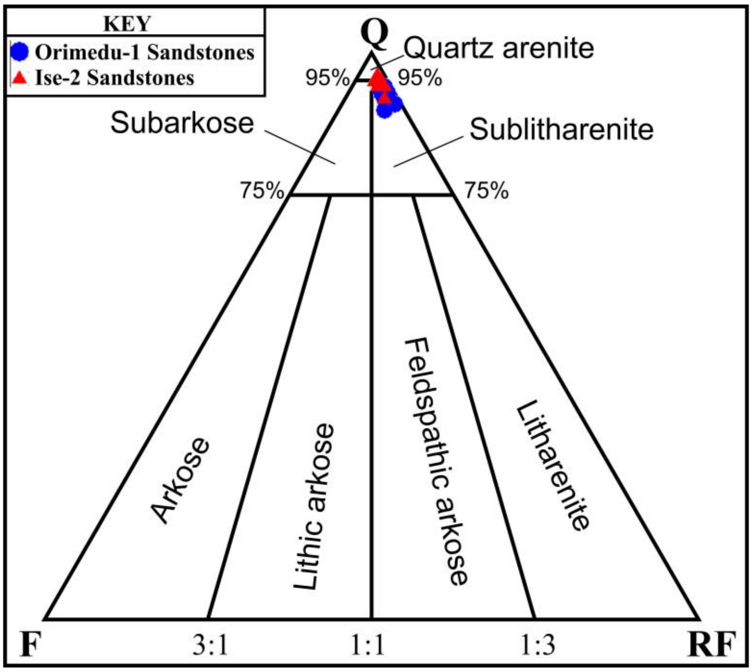

Figure 13: Sandstone classification of the southern and northern traverses of the study area after McBride (1963).

Provenance: Some petrographic data have been widely used and recognised (Blatt, 1967; Dickinson, 1970; Pettijohn et al., 1972) as a reliable tool for defining the origin or provenance of ancient terrigenous sand deposit. Most mineral grains that are chemically less stable than quartz are therefore eliminated (Johnson et al. 1988). Mineral constituents plotted on quartz-feldspar-lithoclast (QFL) and quartz-feldspar-rock (QFR) diagrams of Dickinson and Suczek (1979) and Suttner *et al.* (1981) (Figure 7-9) suggest metamorphic humid, craton interior and continental provenance environments for the sandstones. This suggest significant supply of sediments into the basin in the early Cretaceous from the weathered crystalline basement rocks made up of Migmatite – Gneiss Complex, Schist Belt (Metasedimentary and Metavolcanic rocks) and Older Granites (Pan African granitoids) in the Southwestern part of

Nigeria. Mineral grains are generally sub-angular to sub-rounded with few rounded ones showing textural and mineralogical sub mature to mature rocks that have been transported a considerable distance from their sources leading to the wearing-away of their edges and dissolution or disintegration of less resistant minerals. In the quartz, polycrystalline grains with strained and undulose extinction features constitute about 63% more abundant than the monocrystalline grain. This also indicates the fact that large percentage of the sandstones are source from metamorphic origin with some granitic source (Blatt, and Christie, 1963, Priscilla Chima et al 2018). Sublitharenite and quartz arenites are mostly products of multiple recycling and intense weathering due to long distance transportation.

Zircon, Tourmaline, Rutile, Garnet, Sillimanite and Apatite are the main heavy minerals recovered from the samples. High percentage of zircon, tourmaline, rutile and apatite suggest a source from an acid igneous rock and presence of garnet and sillimanite point to metamorphic origin while rounded grains of rutile, tourmaline, zircon is commonly due to reworked sediments (Feo-codecido 1956). These observed heavy minerals further support the significant supply of sediment from the Migmatite – Gneiss Complex, and Older Granites (Pan African granitoids facies of the surrounding southwestern crystalline basement rocks. The zircon-Tourmaline-rutile (ZTR) index represented by Zircon + Tourmaline + Rutile / Total No of Non-opaque heavy minerals after Hubert's (1962) can also be further used to evaluate the mineralogy maturity of a sandstones. ZTR < 75% implies immature to sub mature sediments and ZTR > 75% indicates mineralogically matured sediments. All the sandstones from both Orimedu-1 and Ise-2 wells except one have ZTR index ranging from 62 % – 74 % which is an indicator that the rocks are sub mature.

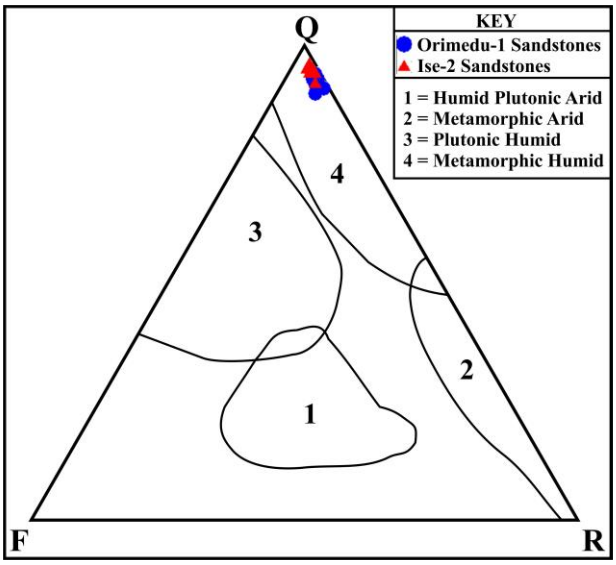

Figure 8: QRF ternary plot showing the paleoclimatic setting on the source rock for Turonian-Coniacian sandstones (after Suttner et al., 1981).

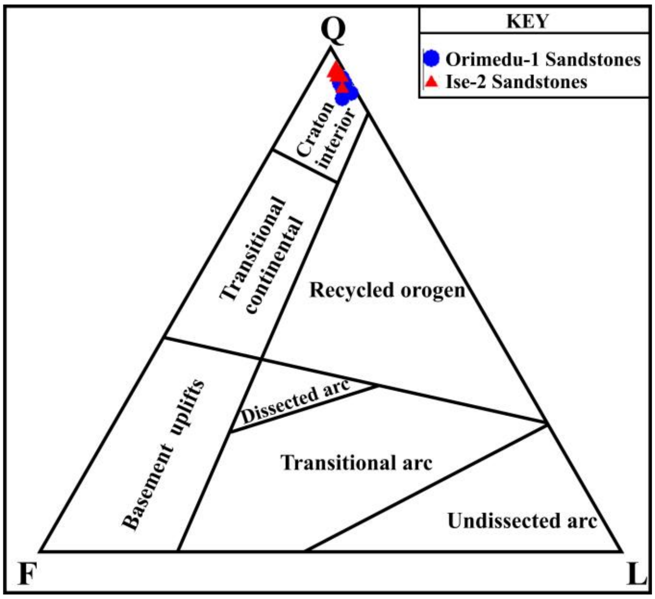

Figure 8: Provenance discrimination diagrams for Turonian-Coniacian sandstones, Dahomey Basin (after Dickinson et al 1983)

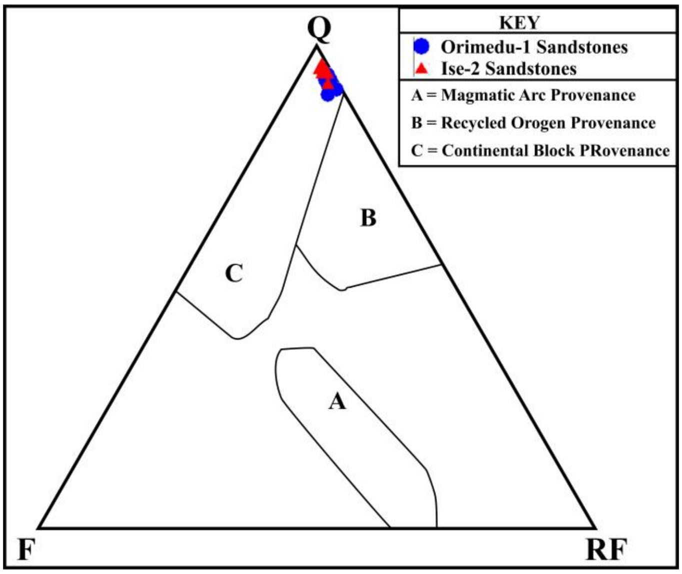

Figure 9: QFRF plot showing paleotectonic setting on the source rock for Turonian-Coniacian sandstones, Dahomey Basin (after Dickinson and Suczek 1979)

Paleoenvironments: Turonian-Coniacian sandstones from the studied wells are interbeded with shales. Physical assessment of the sandstones shows they are clean, loose, medium to coarse grained, moderately sorted, sub angular to sub rounded. The sandstones and shales interbeds in the lithologic log obviously reveals that the rock assemblages are products of many environmental factors or conditions pointing to depositional environments ranging from continental settings to marine. This is because sandstones are generally products of disturbed environment such as aeolian, beach, fluvial, delta while quite waters are commonly responsible for depositing clays, mudrocks or shale such as lacustrine, shallow to deep water.

Grain size is a fundamental property of sediment particles that proffer important clues to the sediment provenance, transport history and depositional conditions (Folk and Ward, 1957; Friedman, 1979; Bui *et al.* 1990). The average grain size mean and sorting indicated that all the sandstones are predominantly coarse grained and moderately sorted except for a sample in Orimedu-1 well. Skewness and kurtosis value range from 0.13 – 0.46 (Phi) averaging 0.23 and 0.62 – 0.92 (Phi) averaging 0.82 (Phi) respectively suggesting that the sandstones are very positively skewed and mesokurtic to platykurtic. These two parameters indicate a medium energy of transportation likened to reworked sediments of middle to lower river regime or beach settings (Friedman, 1979 and Ojo, 2012). Moderate sorting and positive skewness have been used as an indicators of low energy environment characterized by differential deposition with fairly consistent current energy typical of fluvial and beach environments (Selley, 1985 and Tucker, 1988).

Multivariate parameters from grain size (Table 4) reveals that the sandstones have input from both shallow marine and fluvial paleoenvironments suggesting a fluvio-deltaic depositional environment for the sandstones.

Table 4: Summary of multivariate grain-size analysis.

Samples	$\mathbf{Y_{beach:Shallow\ Marine}}$	$\mathbf{Y_{Fluvial:Shallow\ Marine}}$

	Results	Interpretation	Results	Interpretation
Orimedu-1				
OR-1	65.8734	Shallow marine	-4.4671	Shallow marine
OR-2	66.3302	Shallow marine	-2.0613	Shallow marine
0R-3	116.3888	Shallow marine	-9.4105	Fluvial
OR-4	90.9567	Shallow marine	-8.8675	Fluvial
OR-5	68.7873	Shallow marine	-6.7211	Shallow marine
OR-6	99.2172	Shallow marine	-9.3918	Fluvial
OR-7	66.8817	Shallow marine	-6.8022	Shallow marine
OR-8	99.2172	Shallow marine	-9.3918	Fluvial
OR-9	91.6102	Shallow marine	-6.6323	Shallow marine
Ise-2				
2350-2490	62.9252	Beach	-6.0366	Shallow marine
2500-2550	63.2885	Beach	-5.9745	Shallow marine
2600-2670	88.8671	Shallow marine	-9.4688	Fluvial
2780-2800	85.3683	Shallow marine	-8.3560	Fluvial
2830-2890	68.8374	Shallow marine	-6.8116	Shallow marine
2910-2950	88.9208	Shallow marine	-8.4536	Fluvial
2950-3030	64.2863	Beach	-6.9138	Shallow marine
3410-3500	63.8256	Beach	-5.9823	Shallow marine
(Y < 65.3650= Beach, Y > 65.3650= Shallow Marine and Y<-7.419= Fluvial, Y>-7.419= Shallow Marine after Sahu 1964)				

More statistical variables such as Kurtosis versus skewness and standard deviation against mean and skewness (Figure 10-12) of Friedman (1967, 1979), and Ojo, (2012) suggests a predominance of fluvial origin for all the sandstones.

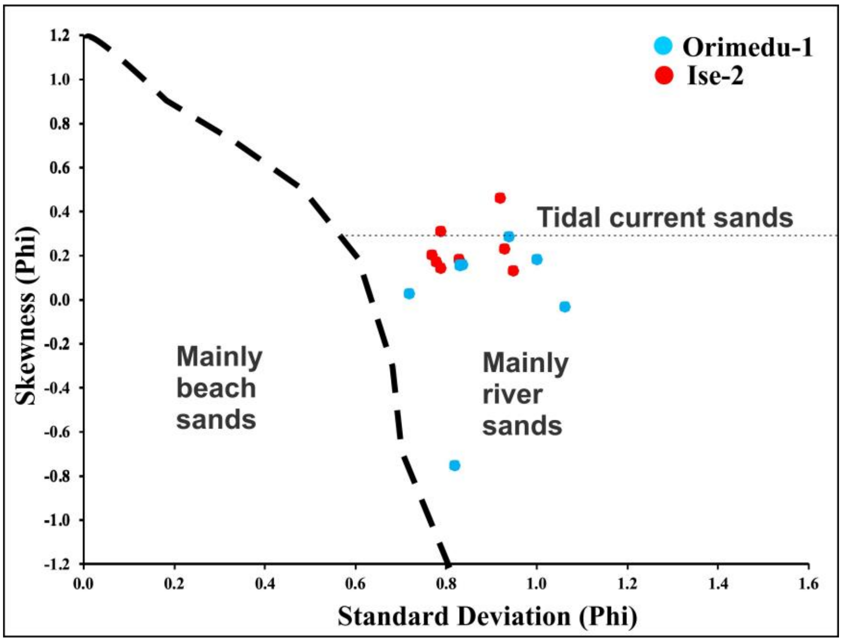

Figure 10: Grain-size bivariate plot of Standard deviation vs skewness showing fields in which beach and river sands plot. (Modified from Friedman, 1967)

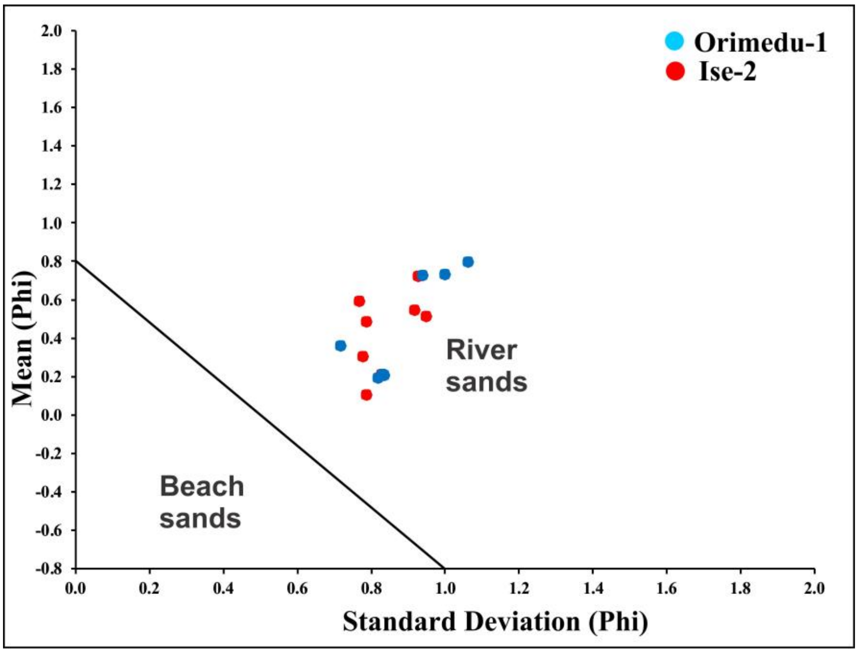

Figure 11: Plot of mean size versus sorting

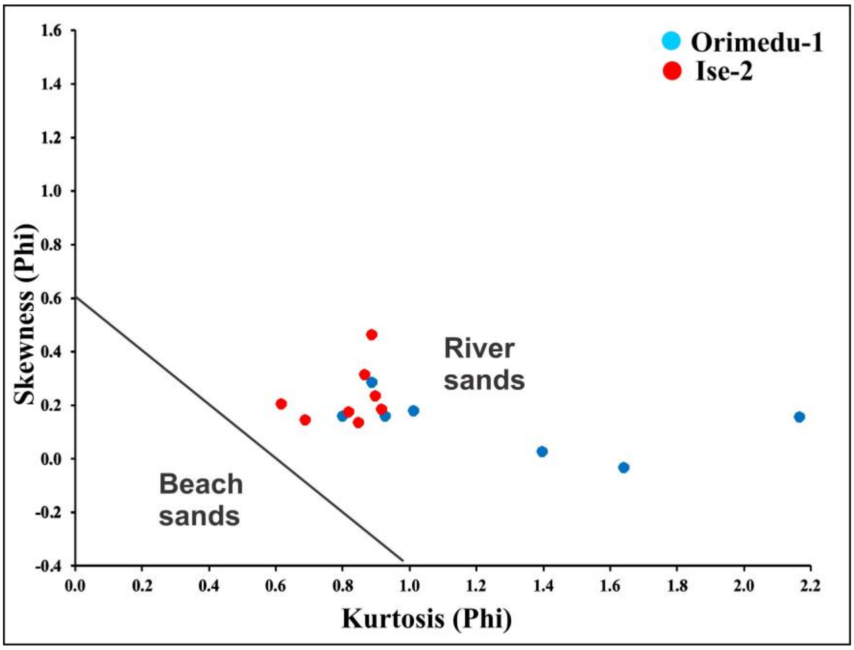

Fig 12: Scatter plot of skewness against Kurtosis. (Friedman 1961, 1979)

Reservoir Potential of Turonian-Coniacian Sandstones

Petroleum system indicator like bitumen seepages, mature Cenomanian source rocks and current production of oil and gas in the offshore area of the basin (Adeoye et al., 2020) has necessitated evaluation of available potential reservoir rocks such as Turonian-Coniacian sandstones for successful petroleum exploitation. Morealso that Aje Field in the deep-water area of the basin has been reported along neighbouring oil and field such as Espoir and Belier fields of Cote d'Ivoire and Seme Field of Benin in the Gulf of Guinea province to have post-transform Albian and Cenomanian-Maastrichtian marginal marine to turbidite potential clastic reservoir sections (Tucker, 1992 and Macgregor et al. 2003). The textural and mineralogy properties of Turonian – Coniacian sandstones in this study will serves as useful information for preliminary assessment of effects of diagenesis and depositional environments on porosity and permeability distribution (Sonibare, 2011). This predictive technique of estimating porosity and permeability is a good tool for hydrocarbon reservoir studies when coupled with cores, well-logs, well test analysis and production data at the exploration and development stage. The composition, texture, and sedimentary structures also control production (Berg, 1986).

The sandstones are coarse grained and moderately to well sorted quartz arenites and such have preserved porosity better than fine grained and poorly sorted facie under similar environmental conditions while those with high clay content such as feldspathic sandstones, lithic arkose or arkose are more susceptible to diagenetic alteration that commonly destroy permeability through cementation during burial (McBride, 1963; Folk, 1974; Ojo, 2012). Cementation reduces permeability quality of sandstones and thereby reduces their reservoir potentials. Undulose extinction exhibited by the quartz grains could be attributed to strain or grain fracturing inherited from by the sediment from source or from mechanical compaction during burial (Taylor, 1950; Basu et al., 1975). Diagenetic alteration due to compaction is more supported by presence of over 60% polycrystalline grain, few matrixes and little quartz growth in sandstones from Orimedu-1 at the burial depth of 1182m than cementation while at 2780m in Ise-2 cementation is expected to increase due to higher temperature.

Empirical porosity and permeability obtained from grain size-based petrophysical studies (Sonibare, 2011- unpublished MSc thesis) suggest that porosity reduction is predominantly due to mechanical compaction. The depositional or original porosity values from Scherer 1987 for TC sandstones is generally 33.6% except for one poorly sorted with 30.7% and at present-day the porosity range between 18.7% and 25.8% averaging 21.3% and reduction follows the burial trend. Shallow intervals have better porosity value (Table 4) than the deeper units with the highest value in Orimedu-1 where cementation was suspected to be low. This porosity values are generally good for a petroleum reservoir. Kozeny-Carman depositional or original permeability ($K_{ok\text{-}c}$ = 26.61 – 82.08D averaging 45.32D; $K_{pk\text{-}c}$ = 9.23 – 33.17D, averaging 18.81D), and Berg depositional or original permeability (K_{oB} = 19.91 – 89.25D averaging 48.75D; K_{pB} = 9.23 – 33.17D, averaging 5.82D).

Generally, the mean permeability values (measured in Darcy) calculated for Kozeny-Carman model are higher than the corresponding permeabilities obtained for Berg model, except for the depositional or original porosity in which Berg model permeability is much higher than the Kozeny-Carman model.Kozeny-Carman and Berg model for empirical prediction of porosity and permeability distribution were employed to have an idea of their potential as reservoir rocks.

The preliminary porosity and permeability of Turonian-Coniacian sandstones inferred from grain size distribution, structure, mineralogy and empirically suggest that the sandstones have good potential as a reservoir rocks but the properties are not uniformly distributed across the basin.

CONCLUSIONS

The granulometric and petrographic studies of the Turonian to Coniacian (TC) sandstones from two exploratory wells (Orimedu-1 and Ise-2) around the eastern or present coastal environments of Dahomey basin, south western Nigeria reveals that:

i. Turonian-Coniacian sandstones across the coastline ranges from sublitharenite to quartz-arenites reflecting their mineralogical and textural maturity as sub mature to mature and further confirmed by Zircon-Tourmaline-Rutile (ZTR) index value of 62 % – 74 %.
ii. Sediments source of supply into the basin ranges from the continental craton interior with highest from humid metamorphic origin followed by acid igneous and reworked sediments.
iii. Provenance indicators favour the Migmatite – Gneiss Complex, and Older Granites (Pan African granitoids facies) crystalline basement rock of southwestern Nigeria.
iv. Turonian-Coniacian are coarse grained, moderately sorted, sub-angular to sub-rounded grain indicating exposure to long distance transportation.

v. Their moderate sorting and positive skewness point to medium to low energy environment characterized by differential deposition with fairly consistent current energy typical of fluvial and beach environments.

vi. There are input from shallow marine and fluvial paleoenvironments typical of fluvio-deltaic depositional settings. Most statistical variables favoured dominance of fluvial origin for all the sandstones.

vii. Turonian-Coniacian sandstones in Dahomey Basin have good quality favourable for a potential reservoir rock.

REFERENCES

Adediran, S. A., and Adegoke, O. S., 1987, Evolution of the sedimentary basins of the Gulf of Guinea. In: Current Research in Africa Earth Sciences, Matheis and Schandeimeier eds. Balkema, Rotterdam, p. 283 - 286.

Adegoke, O. S., 1969, Eocene stratigraphy of southern Nigeria: Memoire. Bureau. Recherche. Geol. Min., no. 69, p. 23-46.

Adekeye O. A., Gebhardt, H., Akande, S. O., Adeoye, J. A., Abdulkadir, I. A. 2019: Biostratigraphic Analysis of the Cretaceous Abeokuta Group in the Eastern Dahomey Basin, Southwestern Nigeria. Journal of African Earth Sciences 152 (2019) 171–183.

Ako, B. D., Adegoke, O. S., and Petters, S. W., 1980, cf. Stratigraphy of the Oshosun Formation in South-Western Nigeria. Journal of Mining and Geology, v.17, p. 97 - 106.

Basu, A., Young, S.W., Suttner, L.J., James, W.C. and Mack, G.H. (1975). Re-evaluation of the use of undulatory extinction and polycrystallinity of detrital quartz for provenance interpretation. Journal of Sedimentary Geology, 45, 873-882.

Beard, D.C. and Weyl, P.K. 1973. Influence of texture on porosity and permeability of unconsolidated sand. AAPG Bulletin, 57, 349–369.Berg, R. R. 1970. Method for determining permeability from reservoir rock properties. In: S.R. Ogilvie, S. Cuddy, C. Lindsay and A. Hurst (Editors), Novel methods of permeability prediction from NMR tool data. Submitted to DIALOG September, 2002, pp1-14. Berg, 1986).

Blatt, H., 1967, Provenance determinations and recycling of sediments: Journal of Sedimentary Petrology, v. 37, p. 1311–1320.

Blatt, H., and Christie, J. M., 1963: Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks. Journal of Sedimentary Petrology, 1963, 33, 559-579.

Brownfield, M. E., and Charpentier, R. R., 2006, Geology and Total Petroleum Systems of the Gulf of Guinea Province of west Africa: U.S Geological Survey Bulletin 2207-C, p.32.

Bui E. N., Mazullo J., and Wilding L. P., 1990, Using quartz grain size and shape analysis to distinguish between aeolian and fluvial deposits in the Dallol Bosso of Niger (West Africa). Earth Surface Processes and Landforms v.14, p. 157 – 166.

Carman, P. C. 1937. Fluid flow through granular beds. In: F.K. Boadu (Editor), Hydraulic conductivity of soils from grain-size distribution: new models. Journal of Geotechnical and Geoenvironmental Engineering, (8)126, 739-746.Carman, 1937

Dickinson, W. R and Suczek, C. A., 1979. Plate tectonics and sandstone composition. Am. Assoc. Pet. Geol. Bull. 63, 2164-2172.Dickinson, W.R., 1970, Interpreting detrital modes of greywacke and arkose: Journal of Sedimentary Petrology, v. 40, p. 695–707.

Dickinson, W. R., L.S. Beard, G.R. Brakenridge, J. L. Erjavec, R.C. Ferguson, K.F. Inman, R.A. Knepp, F.A. Lindberg, and P.T. Ryberg. 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. GSA Bulletin 94 (2): 222–235.

Feo-Codecico, G. 1956: Heavy mineral techniques and their application to Venezuelan Stratigraphy. American Association of Petroleum Geologist Bull., Vol. 40, 948–1000.

Folks, R. L. 1974, Petrology of sedimentary rocks. Hemphil, Austin, Texas, p. 182.

Folks, R. L., and Ward, W., 1957, Brazes river bar: A study of the significance of grain size parameters. Journal of Sedimentary Petrology, v.27, p. 3 - 26.

Freidman, G. M. 1979, Differences in size distribution of populations of particles among sands of various origin. Sedimentology, v. 20, p. 3 - 32.

Friedman, G. M. 1961: Distinction between dune, beach and river sands from their textural characteristics. Journal of Sed. Petrol., Vol. 70, 737–753.

Friedman, G. M. 1967, Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands. Journal of sedimentary petrology, v.37, p. 327 - 354.

Adeoye, J. A., Akande S. O., Adekeye, O. A., Sonibare W. A., Ondrak R., Dominik W., Erdtmann B. D. and Neeka J. (2020): Source Rock Maturity and Petroleum Generation in the Dahomey Basin SW Nigeria: Insights from Geologic and Geochemical Modelling. Journal of Petroleum Science and Engineering 195 107844. https://doi.org/10.1016/j.petrol.2020.107844.

Johnson, M. J., Stallard, R. F. and R. H. Meade, 1988, First cycle quartz arenites in the Orinoco River basin, Venezuela and Colombia: Journal of Geology, v.96, p. 263 - 277.Kozeny, 1927 Macgregor et al. 2003

McBride, E. F., 1963, A classification of common sandstone. Journal of Sedimentary Petrology, v.33, no. 3, p. 664 - 669.

Ojo O. J., 2012, Depositional Environments and Petrographic Characteristics of Bida Formation around Share-Pategi, Northern Bida Basin, Nigeria. Journal of Geography and Geology v. 4, no. 1, p. 224 – 241.Omatsola and Adegoke, 1981

Onuoha, K. M. and Ofoegbu, C. O., 1988, Subsidence and evolution of Nigeria's continental margin: implications of data from Afowo-1 well. Marine and Petroleum Geology, v. 5, p. 175 – 181.

Pettijohn, F. J., Potter, P. E., and Siever, R., 1972, Sand and Sandstone: Berlin, Springer-Verlag, 618 p.

Priscilla C, Christopher B, Kuiwu L, and Oswald G, 2018: Petrography, modal composition and tectonic provenance of some selected sandstones from the Molteno, Elliot and Clarens Formations, Karoo Supergroup, in the Eastern Cape Province, South Africa Open Geosciences, 10:821–833.

Scherer, M. 1987. Parameters influencing porosity and in sandstones: A model for sandstone porosity prediction. In: D.W. Waples (Editor), Evolution of sandstone porosity through ime: The Modified Scherer Model: A calculation method applicable to 1-D maturity modelling and perhaps reservoir prediction. Natural Resources Research, (4)11, 257-272.Selley, R. C. 1985, Ancient Sedimentary Environment, third ed. Cornell University Press, Ithaca, NY, p. 317.

Sonibare, W. A., Mikeš, D., Scheck-Wenderoth, M., and Steel, R. (2011), Proposal for 3D basin analysis and petroleum system/facies modelling of Block 7/Area C (Western Bredasdorp Basin), Southern offshore of South Africa; delivered at the Geosynthesis Conference and Exhibition, CTICC, Cape Town, South Africa (30 August - 2 September 2011).

Suttner, L.J., Basu, A., Mack, G.H. (1981), “Climate and the origin of quartz arenites”, Journal of Sedimentary Petrology 51, 235-246.

Taylor, J. M. (1950). Pore-space reduction in sandstones. AAPG Bulletin, 34(4), 701-716.

Tucker, J. W. 1992, Aspects of the Tano Basin stratigraphy revealed by recent drilling in Ghana. Geologie Africaine. Proceedings of the 1st Conference on the Stratigraphy and Palaeogeography of West African Sedimentary Basins, Libreville, 6-8 May 1991, Bulletin des Recherches Exploration-Production Elf Aquitaine, v. 13, p. 153 - 159.

Tucker, M. E. 1988, Sedimentary Petrology, Blackswell Scientific Publication, Great Britain, p. 235.Waples, 2002