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Provenance and Paleoenvironments reconstruction of Sandstones from Onshore Dahomey Basin, Southwestern, Nigeria: Implications for Reservoir Potential

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Abstract

The aquiferous sandstone units in Daniel-1, Olambe and Yakoyo boreholes located in the onshore part of the eastern Dahomey Basin, Southwestern Nigeria, were investigated through grain size, petrography and geochemical studies to evaluate their provenance, paleoenvironments and the preliminary aquifer or reservoir quality of the sandstones. Average mean, standard deviation (sorting), skewness and kurtosis across the three boreholes ranges from 0.37 mm – 1.37 mm, 0.54 mm – 0.82 mm, 0.18 mm – 0.84 mm and 0.89 mm – 2.07 mm respectively suggesting dominance of medium to coarse grain, and moderate to moderately well sorted sandstones. The mineral grain sizes, sorting and sub-angular to sub-rounded shapes indicate a sub-mature texture. Mineralogy reveals average 78 % quartz, 9 % feldspar and 13 % rock fragments typical of sub-arkose to quartz arenites sandstones. Major oxides of SiO_2 ranges from 90.70 – 99.62 %, Al_2O_3 0.49 – 3.34 %, Fe_2O_3 0.07 – 1.65 %, while other oxides are less than 1.0 % further suggesting dominance of quartz mineral grains. Bivariate plots of Th, La, Sc, Co trace elements further revealed dominance of quartz minerals sourced from felsic granitic igneous rock of a passive margin continental basement. The sub-mature to mature textures and mineralogy coupled with their shallow depths of the sandstones at 130 ft – 160 ft are suitable factors that enhances good porosity and permeability in an aquifer or reservoir rock. These are probably the positive attributes favouring the storage and efficient water production of the aquiferous sandstones. They have similar textural and mineralogy features with the Turonian – Coniacian Afowo sandstones reservoir producing oil and gas in the deep subsurface offshore area of the basin and the onshore Tar sand in Nigeria and part of Benin Republic, West Africa.

Keywords: Provenance, Sandstones, Pre-Santonian, Paleoenvironments, Dahomey Basin

1. Introduction

Sandstone reservoir rock, being one of the most porous and permeable sedimentary unit that accommodate free flow of hydrocarbons or water, is an essential component of a petroleum and hydrology systems (Beard and Weyl, 1973 and Adeoye et al., 2022). Groundwater and petroleum are the two most common sourced or explored earth resources in a sedimentary basin. These two resources

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are the basic needs of every society, widely used and accessible to the commonest man across the globe and more critical in a developing country like Nigeria. Sandstone and carbonate rocks are the two potential reservoir rocks or aquiferous units in Nigeria and other West Africa basins but sandstones constitute the main conventional reservoir or aquifer rocks reported so far (Adediran and Adegoke, 1987, Kjemperud et al., 1992, Brownfield and Charpentier, 2006 and Adeoye et al., 2022). The offshore and deepest part of eastern Dahomey Basin, located in the Southwestern Nigeria has been subjected to serious hydrocarbon exploration in the past ten decades. The exploration effort has recently recorded success in the commercial discovery of oil and gas within the Pre-Santonian sandstones reservoir with evidence of an ongoing production by an indigenous oil and gas company (Adekeye et al., 2019). It is also interesting to note that the Pre-Santonian sandstones have been traced beyond the offshore area through the coastline up to the northern fringe or onshore part along Oso-Iwopin road where it is hosting about 42 bbl of bitumen (Adegoke and Ibe, 1982, Enu, 1985 and Adeoye et al., 2022). This Pre-Santonian sandstone whose mineralogy and textural features are distinctly different from the arkosic and poorly sorted Ilaro sandstones is generally believed to be extended to the current study areas where the city of Lagos State and part of Ogun State are densely populated (Figure 1). It is the aquifer hosting most of the best clean waters for domestic use. The assertion that the aquifer is the Pre-Santonian sandstone is not based on biostratigraphic or geochronology evidences but on lithostratigraphy relationship in term of textural and mineralogy characteristics (Adeoye et al., 2022) In order to have access to sustainable water in the fast-growing city of Lagos and suburb, the inhabitants of these expanding settlements had to depend on the drilling of boreholes to tap from the Pre-Santonian sandstone aquifers far beyond the contaminated, salty or iron rich aquifer. The sandstones are exposed, directly overlying the basement, in some localities along Oso-Iwopin road and Onikintibi in the Northern continental area of the basin but became covered up by the Post Santonian sediments oceanward and in Ibafo area (location of Daniel-1 borehole) through Olambe (location of Olambe borehole) and Yakoyo (location of Yakoyo borehole) in Ogun State (Figure 1).

These study locations in the northern part the basin is not explored for petroleum resources but clean water because they are residential areas with rapid development of urban and major cities of Lagos, Ota, Magboro and suburb. The Pre-Santonian sandstones are also shallow and laterally extensive from the onshore or northern part and thickens into the offshore where it's being targeted as hydrocarbon reservoir (Adeoye et al., 2022). It is therefore imperative to evaluate their sedimentology and chemical characteristics through physical description, petrography and geochemistry to unravel the impact of their source, transportation history, paleoenvironments on their reservoir quality.

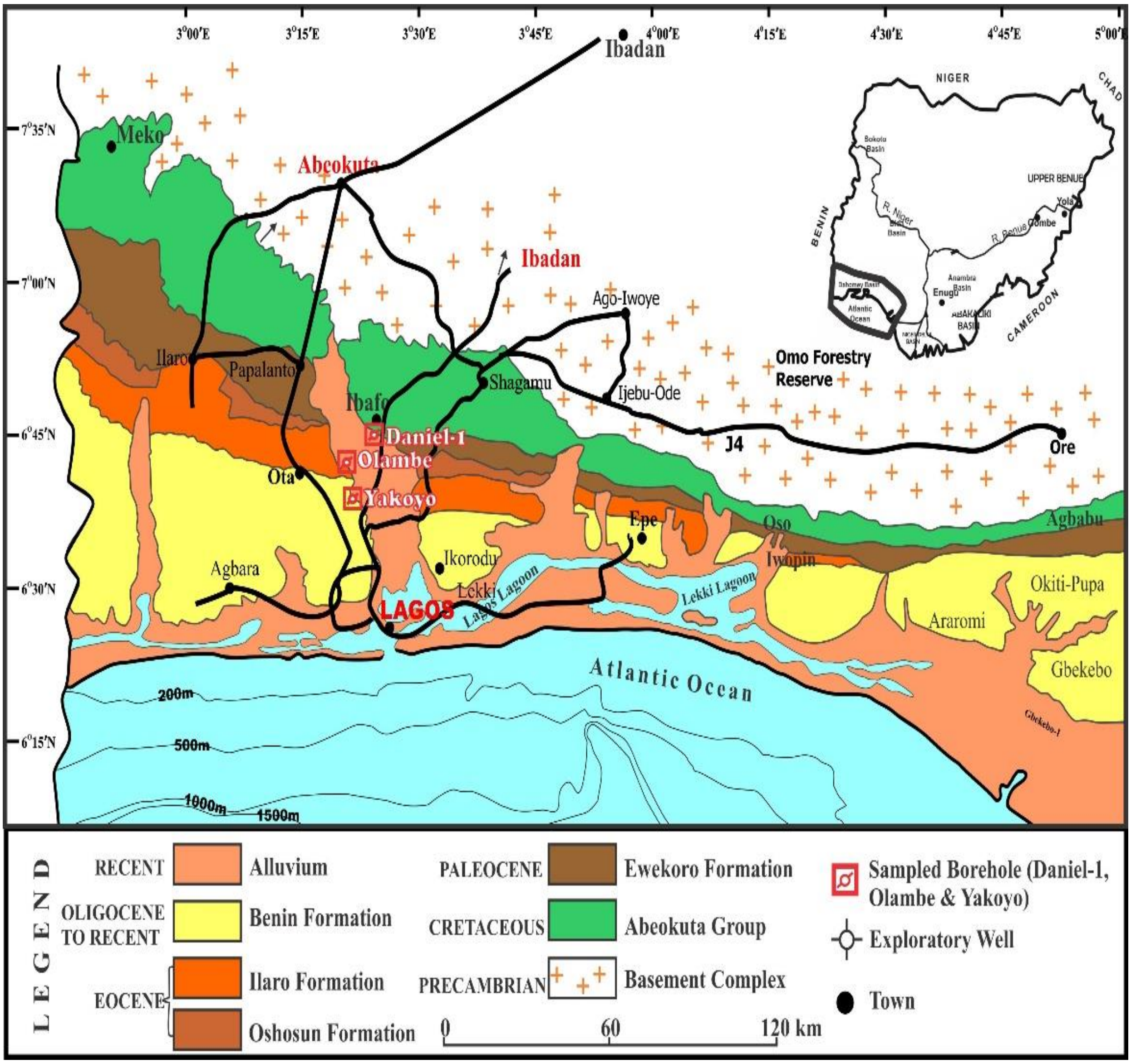

Figure 1: Geological map of Dahomey Basin, southwestern Nigeria showing the location of Daniel-1, Olambe and Yakoyo boreholes at the basin fringe (Modified after Adekeye et al., 2019)

2. Geology and Stratigraphy of Dahomey Basin

Dahomey Basin extends from Nigeria around Okitipupa basement high in the West to the East of Ghana through the Gulf of Guinea and West Africa coastline and from the deep offshore of the Atlantic Ocean tto the onshore where it overlies part of the southwestern Nigeria Precambrian crystalline basement complex (Omatsola and Adegoke, 1981, Adediran and Adegoke, 1987, and Adekeye et al., 2019). The basin's evolution is characterized by tectonic events related to subsidence, rifting, and drifting similar to those of Gulf of Guinea basins including Seme, Tano, Saltpond, Keta and Ivory Coast Basins (Brownfield and Charpentier, 2006). The rifting event has been associated with the continuous separation of Gondwanaland represented by drifting apart of South America and African plates in the Late Jurassic to Early Cretaceous. This Cretaceous tectonism was reported to have been characterized by both block and transform faulting initiated by the St. Paul, Romanche, Chain and Charcot fracture zones forming divergent basins or pull-apart grabens (Blarez and Mascle, 1988). The breaking apart initially caused thick continental clastic deposits consisting of fluvial and some lacustrine facies before further separation of the two plates linking south and north Atlantic oceans thereby creating accommodation for marine sedimentation into the Gulf of Guinea area and further into the failed rift arm known as Benue Trough (Brownfield and Charpentier, 2006).

The Dahomey Basin's depth to basement in the deepest part has been estimated to be about 6km from aeromagnetic data (Oladele and Ayolabi, 2014). Sedimentation began in the Early Cretaceous and span through the Paleogene - Neogene Period and are represented by the initial and older pre-rift continental sediments and syn-rift marine sequences of Neocomian to Albian Ise Formation, succeeded by the Cenomanian-Turonian transgressive marine shales and Turonian to Santonian regressive sandstones of Afowo Formation as Pre-Santonian successions. Post Santonian began with Campanian to Maastrichtian Araromi Formation and was succeeded by the Neogene and Paleogene carbonate, shales and sandstone sequences (Figure 2) (Adegoke, 1969; Ako et al., 1980; Omatsola and Adegoke, 1981; Adediran and Adegoke 1987; Onuoha and Ofoegbu 1988).

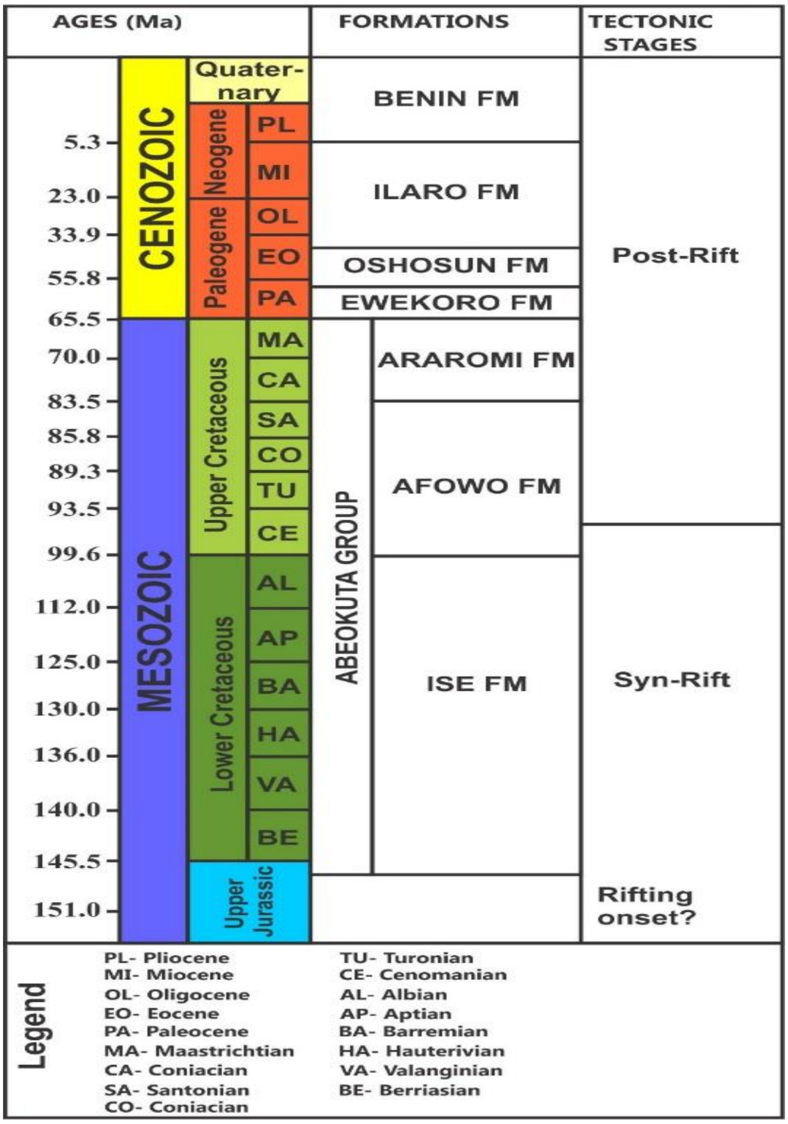

Figure 2: Chronostratigraphic chart of the Dahomey Basin, southwestern Nigeria showing the formations and key tectonic stages (After Adeoye et al., 2020).

3. Materials and Methods

Samples of sandstones collected at 1 m interval during drilling were about hundred (100) out of which the about thirty (30) relevant and loose ones were selected from the three boreholes and subjected to mechanical dry sieving. Dry sieving was carried out with sieve sizes of 3.0, 2, 1.18, 0.6, 0.30, 0.15, 0.075, 0.063 and <0.063 mm arranged vertically in the order of decreasing mesh sizes to obtain data for statistical analysis for the evaluation of grain distributions. 100 g of loose and air-dried sandstone samples were measured with the use of electronic weighing balance and carefully sieved into different sizes which was weighed and analysed. Seventeen of the loose sandstones were selected for thin section petrography. They were first impregnated using epoxy glue for 24 hours and allowed to cure before they were cut to fit on a glass slide and then smoothened with 100 grits carbonrandum in slurry until no more trace of pits and impression were noticeable. Other necessary procedures were carried out and made ready for detail study under a petrological microscope. Twelve samples were selected for heavy minerals and 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 petrographic microscope using transmitted light to observe the minerals. Major oxides and trace elements concentrations of twelve (12) samples taking specifically from the aquifer across the boreholes were determined using inductively coupled plasma optical emission (ICP-OES) and mass spectrometry (ICP-MS) after a Li-metaborate fusion analytical procedure (Jones and Manning, 1994). These analytical methods yielded thirteen major oxides and fifty-one trace elements.

4. Results

4.1. Sedimentology of the Study Area

Three boreholes were drilled for groundwater exploration to depths of 130 ft, 165 ft and 150 ft at the mini-campus of Mountain Top University, Ibafo (Daniel-1 borehole) (Figure 3), Olambe community (Olambe borehole) (Figure 4), and Yakoyo community (Yakoyo borehole) (Figure 5), respectively within densely populated community in Ogun and Lagos States in the northern part of Dahomey Basin (Figure 1).

4.1.1. Daniel-1 Borehole's lithologic Description

Sandstones is the main lthology encounter in Daniel-1 borehole. There two sandstones classified as clayey sandstone and non-clayey sandstone. The clayey sandstones occur at the upper half of the borehole at the depth of 0 – 65 ft. They are poorly sorted and medium to coarse grained texture just above the target aquifer or reservoir. Non-clayey type is medium to fine grain and well sorted occurring at the lower half part of the borehole where most of the aquifers were penetrated. Very thin coals beds are also interbedding the clean sandstone (Figure 3). The non-clayey sandstones are the targeted water reservoir explored for underground water.

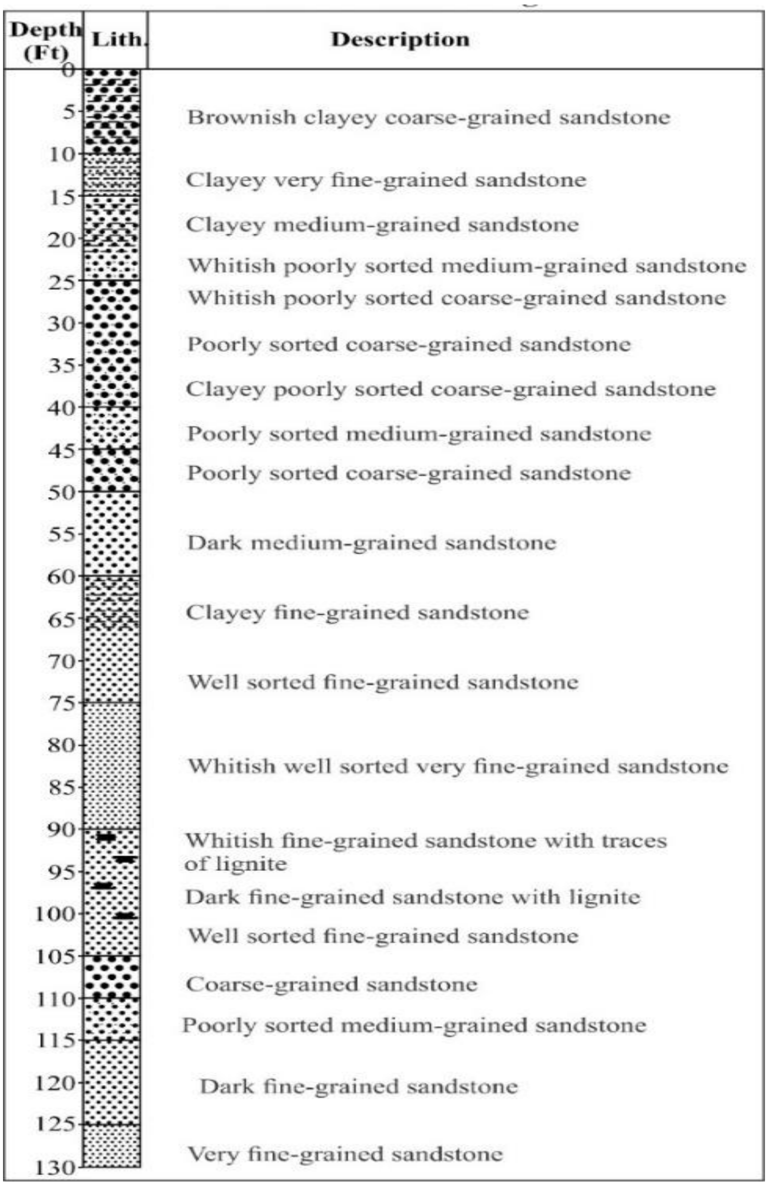

Figure 3: Daniel-1 borehole log at Mountain Top University Campus, Ibafo, Dahomey Basin, southwestern Nigeria.

4.1.2. Olambe Borehole's lithologic Description

Lithologies encountered in Olambe boreholes are laterites, sandstones, and claystones. Sandstones is the most dominant lithology followed by laterite and clayston. Poorly sorted and medium to coarse grain clayey sandstones dominate the upper part of this borehole while non-clayey, well sorted and fine-grained sandstones occupy the lower part. The massive, non-clayey, well sorted and fine-grained sandstones in the lower units form the aquifer unit supplying the underground water (Figure 4).

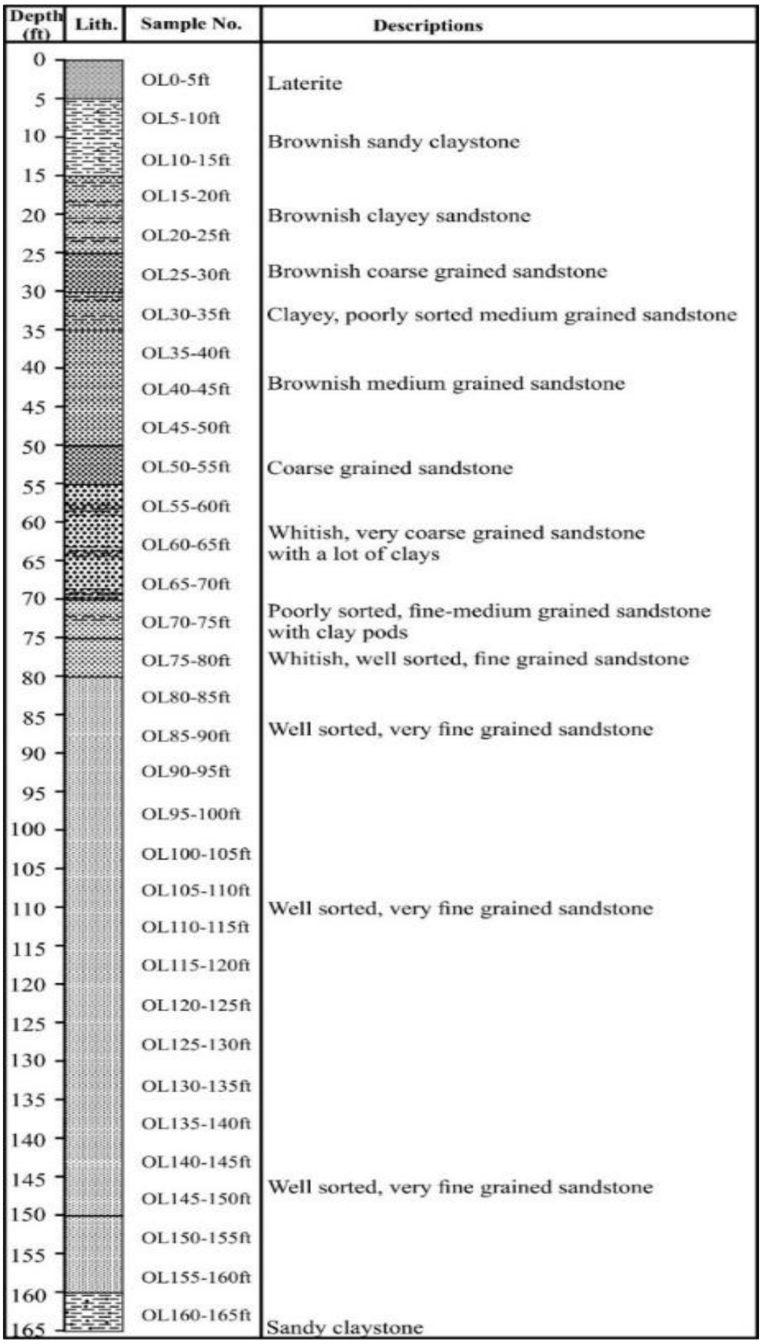

Figure 4: Olambe borehole log in Dahomey Basin, southwestern Nigeria

4.1.3. Yakoyo Borehole's Lithologic Description

Sandstone lateritic sand and claystone are the main constituents of the lithology successions in this borehole (Figure 5). Sandstones form about 90 % of the rock units with fine, medium and coarse textures which are well to moderately sorted except a unit of about 20 ft that is poorly sorted. The target 25 ft thick aquifer of interest forms the basal part of the borehole with well sorted, whitish, medium grained sandstones (Figure 5).

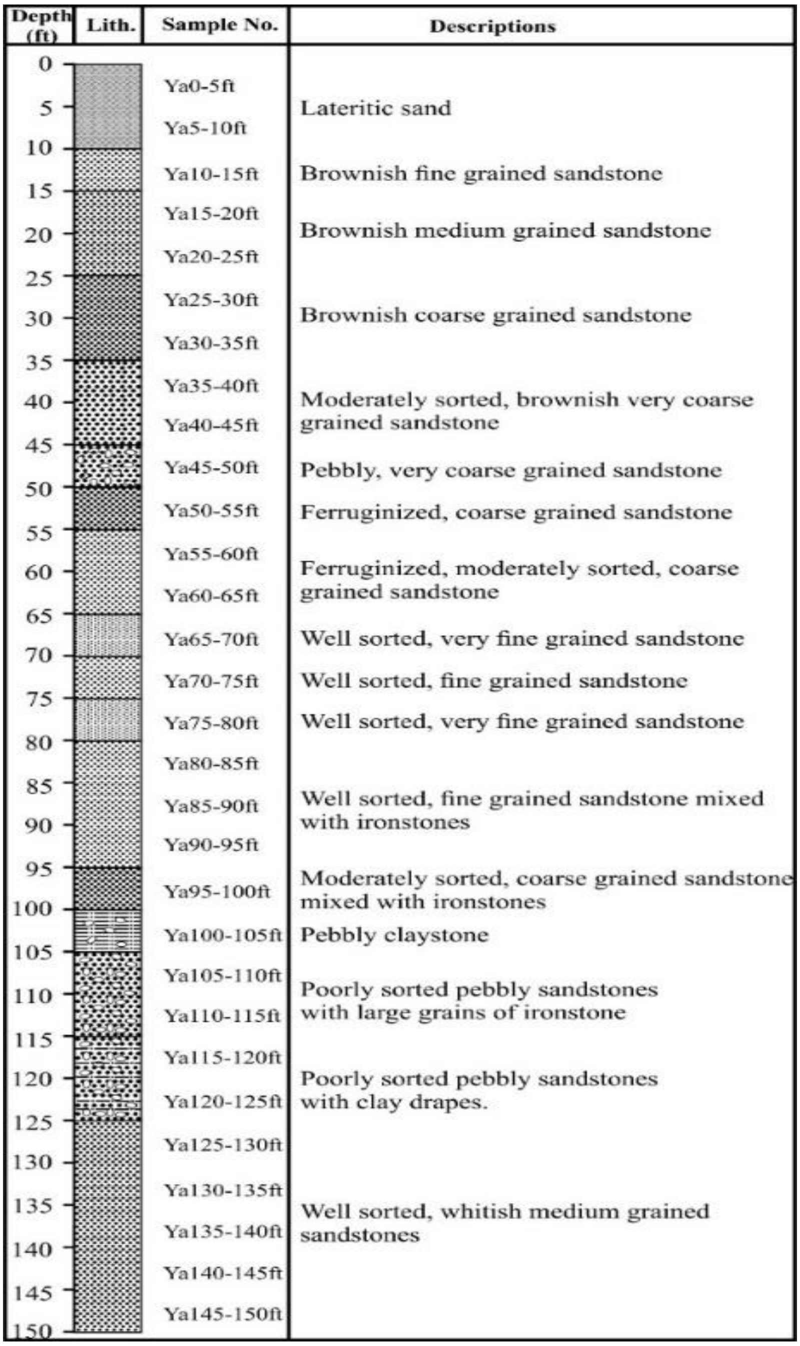

Figure 5 Yakoyo borehole log in Dahomey Basin, southwestern Nigeria

4.2. Grain Size Distribution of the Aquifer Units

Grain size distribution being a quantitative way of assessing textural characteristics of sandstones through statistical variables of mean, standard deviation (sorting), skewness and kurtosis derived from cumulative weight % and percentile (Friedman, 1979) are presented in Table 1. Sediment transportations are commonly by wind, river and glacier under certain climatic condition in different regions of the world where clastic sedimentation processes occurred (Friedman, 1961). These agents of erosion mostly control the rock grain sizes and proffer important clues to the sediment transportation and depositional histories and conditions (Folk and Ward, 1957; Friedman, 1979; Bui et al., 1990).

Samples from Daniel-1 aquferous unit at the depth of 115 -130 ft are generally medium to coarse grained (0.69 – 1.78 mm) and moderately sorted to well sorted (0.40 – 0.97 phi) overlying it is a poorly sorted (1.05 – 10.9 mm) unit containing some clay materials. Olambe's aquifer lie within the depth of 80 – 160 ft and are medium grained (1.06 – 1.87 mm) and moderately sorted to very well sorted (0.30 – 0.80 mm). At 125 – 150 ft depth of aquifer in Yakoyo, the sandstones are coarse grained (-0.42 – 0.46 mm) and are moderately sorted (0.86 – 095 mm).

4.3. Thin Section Petrography

Petrography of the sandstones reveals the constituents, arrangement and shape of mineral present in the rock which are often group as quartz, feldspar and rock fragments or lithoclast in the ternary plot (McBride, 1963). Quartz minerals are the most dominant as seen in the hand specimen and representative photomicrograph (Figure 6a, b, c and d Table 2). There are more monocrystalline than the polycrystalline quartz grains and exhibit less strained to undulose extinction (Figure 6a and Figure 6b).

Table 1: Grain size distribution data and interpretation

SAMPLES	VARIABLES				INTERPRETATION			
DANIEL-1								
	M	**SD**	**S**	**K**	**M**	**SD**	**S**	**K**
DA-7	1.53	0.97	1.19	1.01	Medium	Moderately Sorted	VPS	Mesokurtic
DA-11	0.96	0.96	0.80	0.93	Coarse	Moderately Sorted	VPS	Mesokurtic
DA-14	1.29	1.09	1.18	0.88	Medium	Poorly Sorted	VPS	Platykurtic
DA-18	1.08	0.77	0.58	1.03	Medium	Moderately Sorted	VPS	Mesokurtic
DA-24	1.66	0.40	-0.71	1.16	Medium	Very Well Sorted	VPS	Leptokurtic
DA-27	1.78	0.41	1.02	1.01	Medium	Well Sorted	VPS	Mesokurtic
DA-30	1.72	0.85	0.93	0.81	Medium	Moderately Sorted	VPS	Platykurtic
DA-34	0.69	0.78	0.93	1.33	Coarse	Moderately Sorted	VPS	Leptokurtic
DA-35	1.71	1.05	0.24	0.94	Medium	Poorly Sorted	VPS	Mesokurtic
DA-38	1.15	0.87	0.97	0.72	Medium	Moderately Sorted	VPS	Platykurtic
OLAMBE								
OL-23	-0.03	1.18	0.60	0.92	Very Coarse	Poorly Sorted	VPS	Mesokurtic
OL-27	1.26	0.30	1.65	4.54	Medium	Very Well Sorted	VPS	Extremely Leptokurtic
OL-31	1.42	0.40	1.73	1.47	Medium	Well Sorted	VPS	Leptokurtic
OL-34	1.68	0.33	-1.00	1.97	Medium	Very Well Sorted	VPS	Very Leptokurtic
OL-37	1.64	0.80	-0.59	1.33	Medium	Moderately Sorted	VPS	Leptokurtic
OL-38	1.87	0.52	1.58	1.70	Medium	Moderately Sorted	VPS	Very Leptokurtic
OL-40	1.69	0.52	1.42	3.01	Medium	Moderately Sorted	VPS	Extremely Leptokurtic
OL-43	1.51	0.42	1.28	2.64	Medium	Well Sorted	VPS	Very Leptokurtic
OL-47	1.06	0.42	0.89	1.01	Medium	Well Sorted	VPS	Mesokurtic
YAKOYO								
YA-20	0.92	0.33	0.60	1.73	Coarse	Very Well Sorted	VPS	Very Leptokurtic
YA-21	1.55	0.35	1.59	1.53	Medium	Well Sorted	VPS	Very Leptokurtic
YA-24	1.49	0.52	1.00	1.47	Medium	Moderately Sorted	VPS	Leptokurtic
YA-27	0.42	0.47	0.86	4.23	Coarse	Well Sorted	VPS	Extremely Leptokurtic
YA-31	-0.42	0.49	0.55	1.64	Very Coarse	Well Sorted	VPS	Very Leptokurtic
YA-34	-1.05	0.70	0.79	0.94	Very Coarse	Moderately Sorted	VPS	Mesokurtic
YA-37	0.46	1.09	0.76	1.69	Coarse	Poorly Sorted	VPS	Very Leptokurtic
YA-40	-0.17	0.86	0.75	0.82	Very Coarse	Moderately Sorted	VPS	Platykurtic
YA-43	0.09	0.95	-5.24	0.84	Coarse	Moderately Sorted	VNS	Platykurtic

(M-Mean, SD-Standard Deviation, S-Skewness, K-Kurtosis, VPS- Very Positively skewed, VNS-Very Negatively Skewed).

Table 2: Average modal results of the abundance of framework component of sandstones aquifer in Daniel-1, Olambe and Yakoyo boreholes.

S/N	Samples	Quartz (%)	Feldspar (%)	Rock Fragment (%)
Daniel-1 Borehole				
1	D32	76	11	13
2	D55	66	13	20
3	D80	85	7	8
4	D100	84	10	7
5	D110	88	8	3
6	D115	80	8	12
7	D125	52	12	36
Olambe Borehole				
8	OL70	68	20	12
9	OL80	88	7	5
10	OL100	75	12	12
11	OL120	78	8	14
12	OL125	86	8	5
13	OL140	93	2	4
Yakoyo Borehole				
14	Y65	74	9	16
15	Y70	91	3	6
16	Y100	63	11	26
17	Y150	73	8	18

Quartz mineral grains are predominant representing 98 to 93 % in all the samples. They are sub-angular to sub-rounded in shape with some visible fracture structure that may be due to stress possibly induce through bombardment and collision during transport (Figure 6 a, b, c. and d). Plagioclase feldspar are the most visible feldspar with very few microcline and other rock fragments.

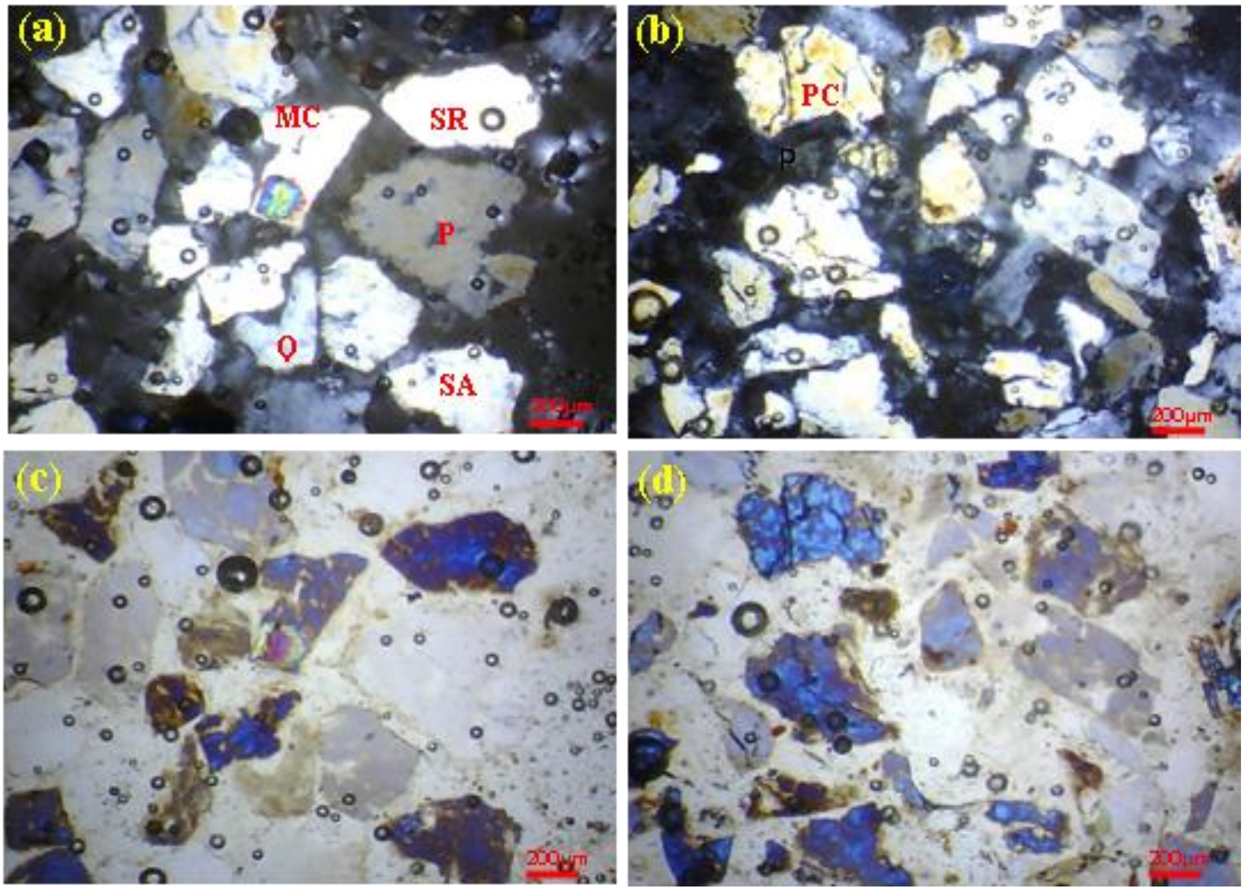

Figure 6: Representative photomicrograph for the sandstones at the study locations showing monocrystalline (MC), polycrystalline (PC), sub-angular (SA) to sub-rounded (SR) quartz grains and P-Plagioclase feldspar

4.4. Heavy Mineral

Heavy minerals are useful and reliable indicator of provenance or source of clastic sediments. The samples consist of opaque and non-opaque minerals. Opaque minerals are dark under the petrographic microscope, and they include hematite, limonite and magnetite. Non-opaque minerals identified are zircon, tourmaline, rutile, garnet, sillimanite and apatite (Figure 7).

Zircon, rutile and tourmaline represent the most dominant heavy minerals across the three locations. They are known to be some of the ultra-stable heavy minerals that can withstand prolonged abrasion and survive many re-workings (Feo-codecido,1956). The percentage of the opaque mineral is more than that of the non-opaque minerals. Heavy minerals suites are good indicator of source-rock. Association of apatite, biotite, hornblende, monazite, rutile, titanite, pink tourmaline, and zircon indicates igneous rock, Augite, chromite, diopside, hypersthene, ilmenite, magnetite, and olivine points to basic igneous rock, Andalusite, garnet, staurolite, topaz, kyanite, sillimanite, and staurolite suggest Metamorphic origin while barite, iron ores, leucoxene, rounded tourmaline, rounded zircon indicates recycled sedimentary rocks. Felsic Igneous rock often contain zircon, apatite and magnetite while tourmaline, staurolite, biotite and muscovite are common in low rank metamorphic rocks and igneous rocks (Mange and Maurer 1992). The heavy minerals are sub-angular to sub-rounded in shape.

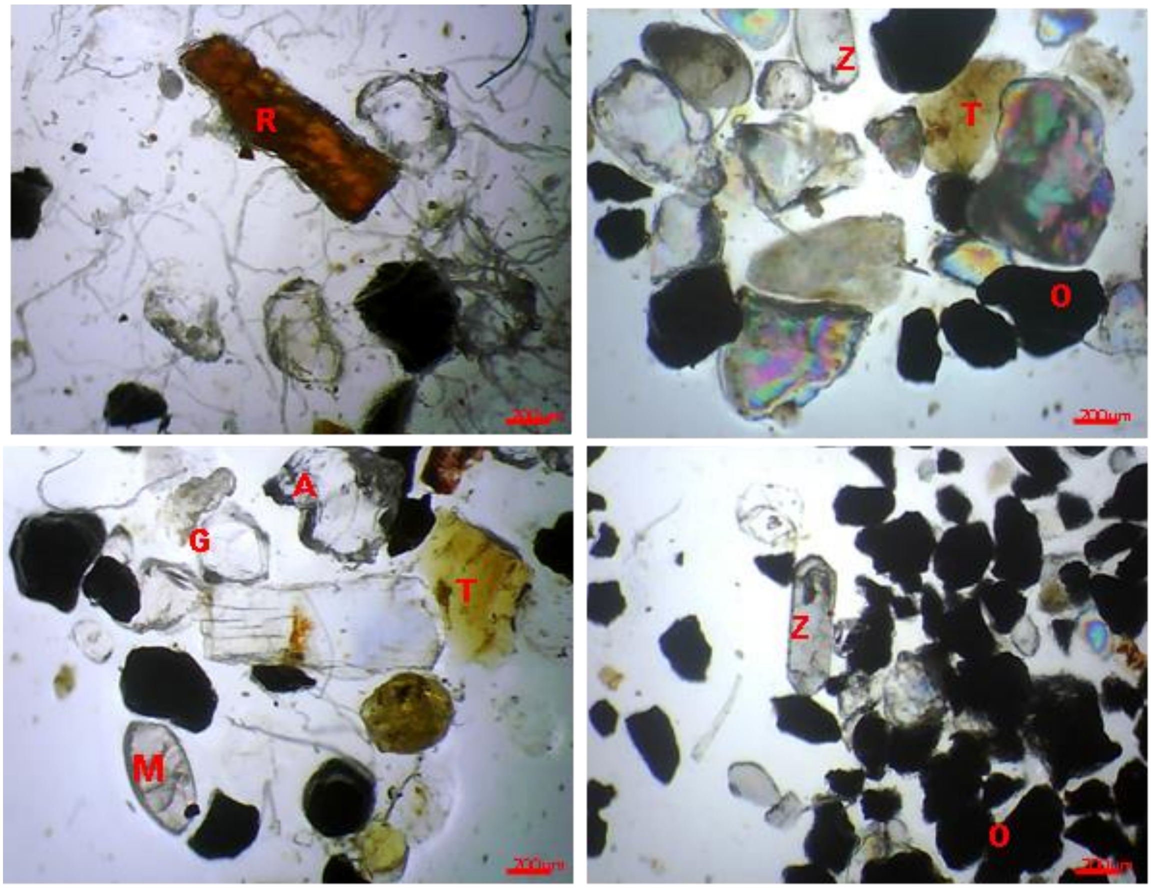

Figure 7: Photomicrograph of the heavy minerals in the aquifer sandstones. Note T- Tourmaline, Z-Zircon, A-Apatite, G-Garnet, R-Rutile, M-Monazite and O-Opaque minerals

4.5. Major Oxides and Trace Elements

Silicon oxide (SiO_2) is the most abundant and dominant oxide in the studied sandstones with concentration ranging from 90.34 to 99.62 % (mean 95.42 %) of the whole oxides. Next to it is the aluminium oxide (Al_2O_3) which ranges from 0.49 to 4.15 % (mean 1.93 %), iron (Fe_2O_3) ranges from 0.19 to 1.65 % (mean 0.66 %) and titanium (TiO_2) ranges from 0.09 to 0.27 % (mean 0.13 %) (Table3). Oxides of Barium, Chromium, Calcium, Potassium, Magnesium, Manganese, Sodium, and

Phosphorous are all significantly little in all the samples (<0.01 %) except for little increase of CaO (0.22 – 0.56 %), K_2O (0.63 – 1.2 %), MgO (0.02 – 0.04%), MnO (0.01 – 0.02 %) and Na_2O (0.38 - 0.96) in Daniel-1 (Table 3). The trace elements that have significant concentration in the sandstones are chromium, barium, zircon, strontium, manganese, vanadium, thorium, iron, lactinum etc. (Table 4).

Table 3 Major Oxides (%) in the sandstone samples

Samples	SiO_2	Al_2O_2	Na_2O	K_2O	MgO	TiO_2	Fe_2O_3	CaO
OLA-70	93.44	3.34	0.01	0.04	0.01	0.25	1.41	0.01
OLA-100	97.36	0.85	0.01	0.01	0.01	0.09	0.22	0.01
OLA-140	94.92	1.73	0.01	0.01	0.01	0.16	0.39	0.01
OLA-155	97.03	0.63	0.01	0.01	0.01	0.09	0.19	0.01
YA-90	97.87	1.14	0.01	0.01	0.01	0.15	1.64	0.01
YA-100	95.2	1.04	0.01	0.01	0.01	0.09	1.65	0.01
YA-120	98.83	0.66	0.01	0.01	0.01	0.05	0.44	0.01
YA-140	99.62	0.49	0.01	0.01	0.01	0.05	0.07	0.01
DAN-90	90.7	4.4	0.96	1.1	0.02	0.12	0.26	0.56
DAN-100	90.34	4.15	0.8	1.17	0.04	0.27	0.76	0.49
DAN-110	96.27	2.37	0.38	0.68	0.02	0.11	0.55	0.22
DAN-125	93.42	2.39	0.42	0.63	0.02	0.18	0.36	0.25

Table 4 Trace elements (ppm) in the sandstone samples

Samples	Rb	Ba	Cr	Mn	Mo	U	Th	V	Zr	Sr	Ni	Co	Fe	La	Sc	Hf	Nb
OLA-70	0.50	16.00	50.00	13.00	0.40	0.55	2.50	35.00	4.50	1.00	0.80	0.20	0.88	2.30	1.50	0.12	0.14
OLA-100	0.10	16.00	3.00	5.00	0.08	0.12	0.70	2.00	1.90	0.50	0.30	0.10	0.10	1.00	0.40	0.05	0.06
OLA-140	0.40	15.00	7.00	8.00	0.14	0.18	1.30	8.00	3.20	1.20	0.80	0.20	0.22	2.40	0.60	0.09	0.13
OLA-155	0.10	17.00	3.00	5.00	0.11	0.12	0.70	3.00	2.30	0.80	0.40	0.10	0.09	1.20	0.30	0.07	0.08
YA-90	0.20	15.00	13.00	9.00	0.13	0.33	1.20	13.00	2.10	1.00	0.40	0.20	1.09	1.50	0.80	0.06	0.12
YA-100	0.10	13.00	12.00	6.00	0.12	0.35	0.80	13.00	1.50	1.30	0.30	0.10	1.13	1.00	0.80	0.05	0.12
YA-120	0.20	17.00	4.00	5.00	0.07	0.18	0.70	4.00	1.70	0.70	0.40	0.20	0.29	1.20	0.40	0.05	0.10
YA-140	0.10	15.00	1.00	5.00	0.05	0.25	0.60	1.00	1.70	0.50	0.40	0.10	0.03	1.30	0.20	0.05	0.06
DAN-90	1.10	34.00	2.00	26.00	0.06	0.14	0.80	2.00	1.60	2.30	0.60	0.40	0.10	2.20	0.20	0.04	0.13
DAN-100	1.70	53.00	4.00	115.00	0.13	0.28	1.90	8.00	1.60	2.40	1.10	1.30	0.38	3.40	0.40	0.05	0.20
DAN-110	1.20	53.00	4.00	108.00	0.13	0.20	1.10	7.00	1.30	1.30	0.80	1.00	0.31	2.10	0.30	0.04	0.11
DAN-125	0.70	29.00	2.00	30.00	0.12	0.11	0.80	3.00	1.70	1.40	0.50	0.30	0.13	1.60	0.20	0.05	0.16

5. Discussion

5.1. Mineralogy of the Sandstones

Mineralogy and chemical composition of sandstones are significantly influenced or controlled by their source (i.e. parent rock, weathering and transportation medium), depositional environments and paleo-conditions (Freidman, 1961). These compositional characteristics are part of the deposited materials that can be inferred from their petrographic and geochemical analyses. Quartz is the dominant mineral grain with average value of about 81% in Olambe and 75% in Yakoyo sandstones and 76% in Daniel-1. Feldspar and other rock fragments are less than 10% and 20% respectively (Table 2). Most of the sandstones in Daniel-1, Olambe and Yakoyo are classified as quartz sub-arkose to sub-litharenite with few quartz arenite, lithic arkose and Feldspathic litharenite (Figure 8). These classifications indicate products of recycling, intense weathering and moderate transportation from the source. The weak minerals such as feldspar has been significantly removed and their mineralogy is suggesting sub-mature to mature.

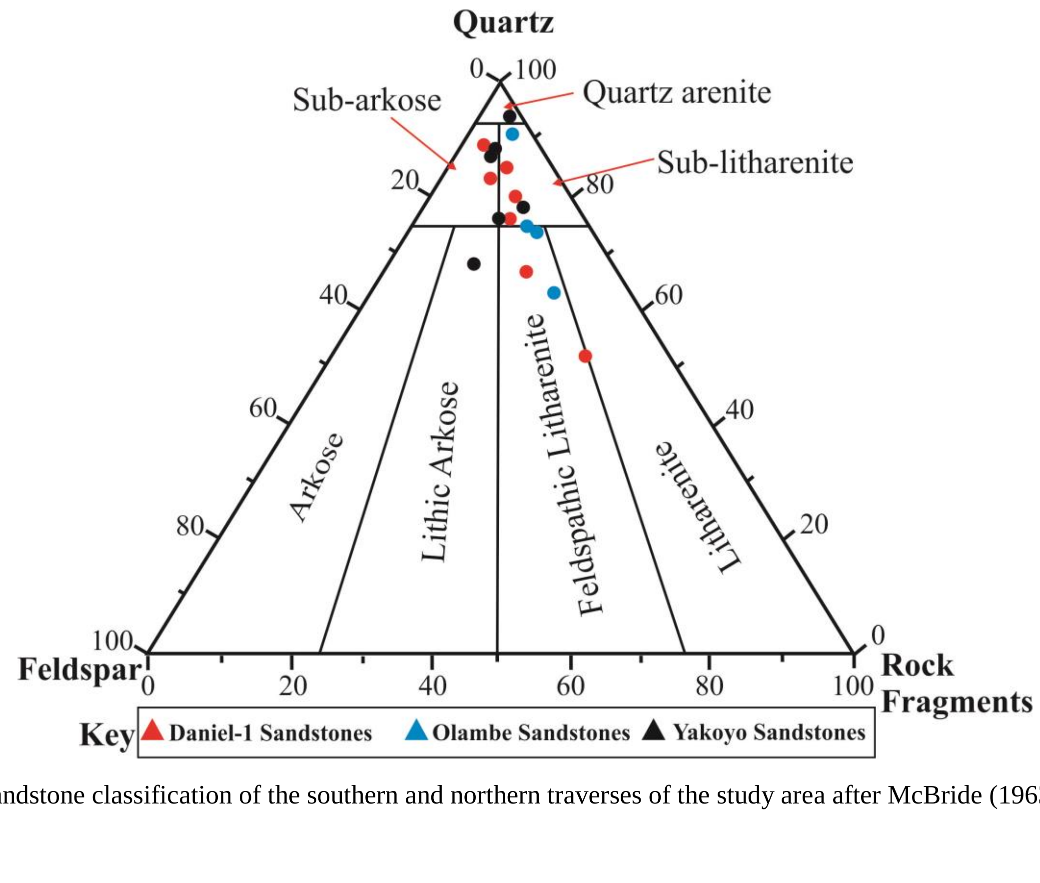

Figure 8: Sandstone classification of the southern and northern traverses of the study area after McBride (1963).

High silica (SiO_2), low Al_2O_3 and very low concentration (<0.01%) of K_2O, MgO, CaO and Na_2O contents in all the sandstones from Daniel-1, Olambe and Yakoyo suggests intense alteration of feldspars and other clay minerals or argillaceous sediments by weathering and reworking. The plot of log (SiO_2/Al_2O_3) vs log (Fe_2O_3/K_2O) after Herron, (1988) reveals that some of Daniel-1 sandstones are sub-arkose corroborating the presence of more aluminum, potassium, magnesium, and sodium oxides commonly found in feldspar while those ones from Olambe and Yakoyo are mainly quartz arenites (Figure 9).

The concentration of oxides of silicon, aluminum, potassium, sodium and iron have also been used to classify sandstones into quartz arenites, greywacke, arkose or lithic arenite (Blatt et al., 1972; Pettijohn et al., 1972; Herron, 1988) and their ratio as well been proposed as guidelines for chemical classification of sandstones (Lindsey, 1999). If log (SiO_2/Al_2O_3) ≥ 1.5, then the sandstone is classified as quartz arenite; If log (SiO_2/Al_2O_3) is < 1, log (K_2O/Na_2O) < 0, it is a Greywacke; and when log (SiO_2/Al_2O_3) is less than 1.5, log (K_2O/Na_2O) ≥ 0 and log ((Fe_2O_3+MgO)/(K_2O+Na_2O)) < 0, the sandstone is classified as Arkose; and lastly when log (SiO_2/Al_2O_3) < 1.5, log (K_2O/Na_2O) < 0 or log ((Fe_2O_3+MgO)/ (K_2O+Na_2O)) ≥ 0, then the sandstone is classified as Lithic arenite (Sub greywacke). These guidelines suggest that most sandstones within the aquifers i.e. Ola-140, Ola-155 in Olambe, Ya-120 and Ya-140 in Yakoyo and Dan-110 and Dan-125 in Daniel-1 are all sub-litharenite. The upper sandstones in Daniel-1 (Dan-90 and Dan-100) (Table 4) have log (SiO_2/Al_2O_3) less than 1.5, log (K_2O/Na_2O) ≥ 0 and log ((Fe_2O_3+MgO)/(K_2O+Na_2O)) < 0 suggesting more of arkosic sandstones in Daniel-1. This is consistent with the plot of log (SiO_2/Al_2O_3) vs log (Fe_2O_3/K_2O) (Figure 9) showing chemical classification of the dominant minerals of the studied sandstones from the study areas. The clay content in the overlying unit above the aquifer in Daniel-1 could be part of the sealing units with an advantage of preventing easy percolation of unwanted materials or pollutant into the aquifers if its sealing properties are effective.

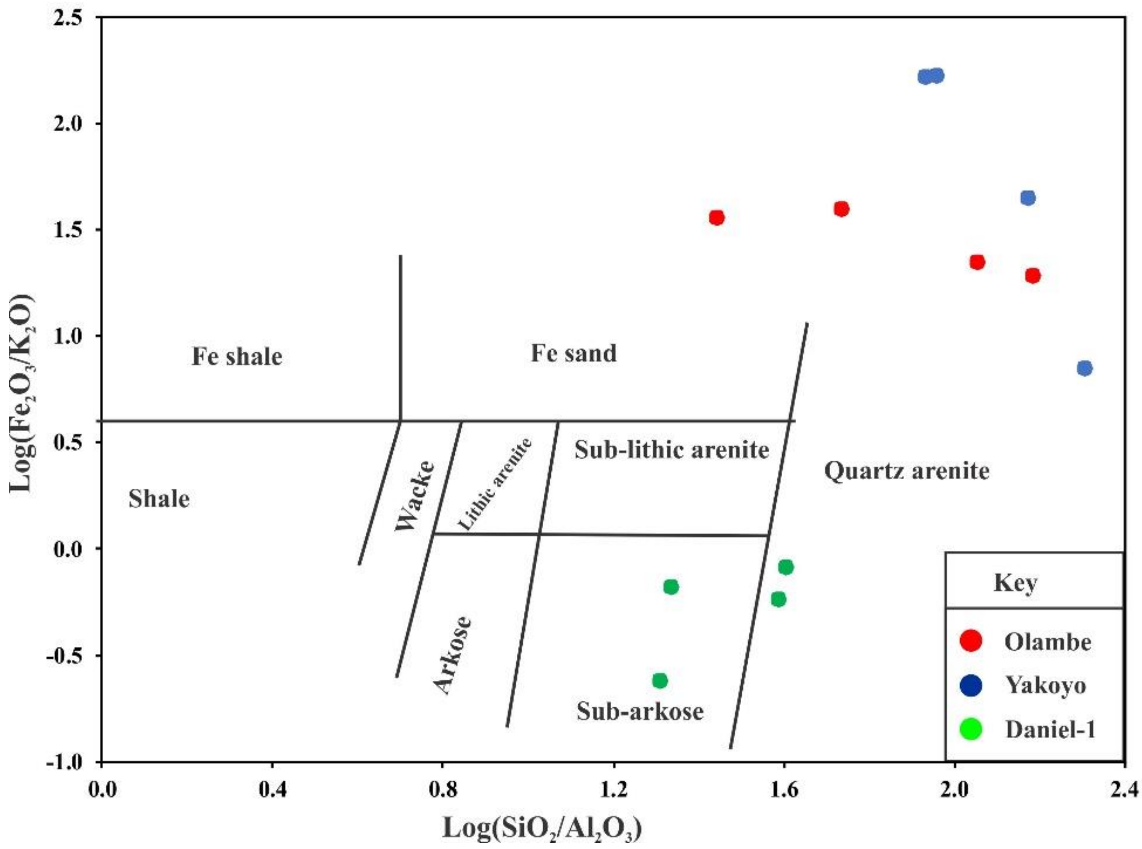

Figure 9: Plots of log (SiO_2/Al_2O_3) vs log (Fe_2O_3/K_2O) showing chemical classification of the dominant minerals of the studied sandstones from the study areas (After Herron, 1988).

Table 5: Guidelines for chemical classification of sandstones (Lindsey, 1999)

Samples	Log (SiO_2/Al_2O_3)	Log (Fe_2O_3+MgO)/(K_2O+Na_2O)	Log(K_2O/Na_2O)	Al_2O_3/TiO_2
OLA-70	1.45	1.45	0.60	13.4
OLA-100	2.06	1.06	0.00	9.4
OLA-140	1.74	1.30	0.00	10.8
OLA-155	2.19	1.00	0.00	7.0
YA-90	1.93	1.92	0.00	7.6
YA-100	1.96	1.92	0.00	11.6
YA-120	2.18	1.35	0.00	13.2
YA-140	2.31	0.60	0.00	9.8
DAN-90	1.31	-0.87	0.06	36.7
DAN-100	1.34	-0.39	0.17	15.4
DAN-110	1.61	-0.27	0.25	21.5
DAN-125	1.59	-0.44	0.18	13.3

5.2. Provenance of the Sandstones

The textural and mineralogy maturity of sandstones are controlled by weathering and transportation effects. Medium to coarse grain and moderately to well sorted textural features of all the sandstones (Figure6 and Table 1) suggest they have been reworked and transported a considerable distance from their source. Clastic mineral grains break down from collisions with one another or river bed leading to sorting of weak minerals from the highly resistant ones (Johnson et al., 1988). More also, the mineral constituents of the sandstones reveal predominant of quartz that are known for high resistance to weathering were classified as sub-arkose and sub-litharenite. The quartz and heavy minerals exhibit sub-angular to sub-rounded shapes giving further credence to long distance movement from source area or were derived from older eroded and reworked sedimentary rocks. This is because most mineral grains that are chemically less stable than quartz are easily eliminated through chemical weathering, abrasion and collision during transportation from their source to the depositional environment. Mechanical weathering of collision and abrasion are responsible for the smoothening of the edges of the once angular quartz and heavy minerals. Heavy minerals of zircon, tourmaline, garnet, rutile and non-opaque minerals in the samples (Figure 7) are commonly sourced from both felsic and mafic igneous rock. The dominant of monocrystalline quartz grain suggests high supply of material from igneous or recycled source (Al-Harbi and Khan, 2008) while the few polycrystalline and sign of stress and fractures on the grains maybe a possible contribution from metamorphic origin.

Major oxides and trace elements geochemistry are also very useful tools in investigating mineral composition, clay minerals and the weathering process a sedimentary rock has been subjected to because the rocks are essentially products of weathering of pre-existing rocks and other prevailing conditions during transportation and deposition (Pettijohn, 1975; Adeoye et al., 2020). As in the case Co/Th against La/Sc (Figure 10), most of the geochemical and mineralogy variables of the sandstones suggest their source to be from felsic rocks such as granites which compose more of silica minerals.

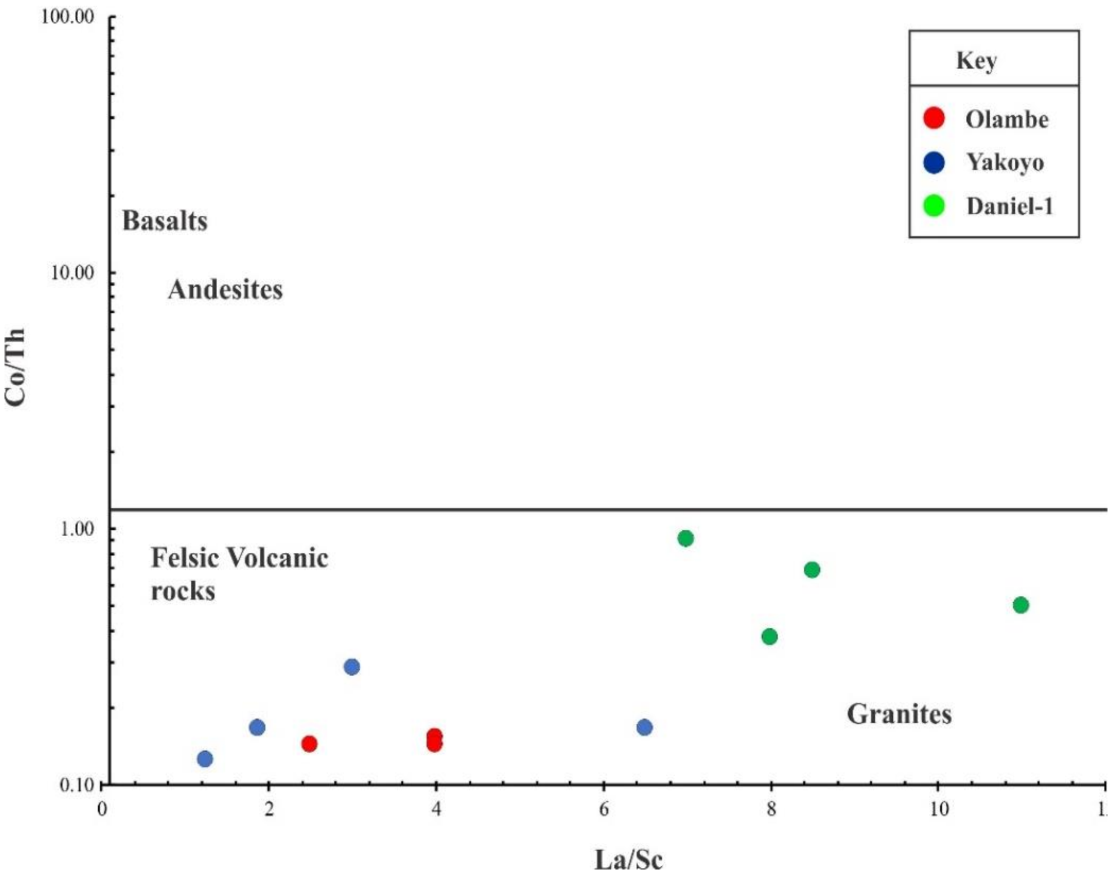

Figure 10: Co/Th ratio vs. La/Sc ratio plot. Average compositions of igneous rocks from Condie (1993) and Gu et al., (2002)

Al_2O_3/TiO_2 ratio is also useful in provenance tool especially in the chemical composition of source rock which ranges from granitic to mixed granitic/basaltic rocks (Amajor, 1987). Previous studies reveal that Al_2O_3/TiO_2 ratio in mafic igneous rock is 3 to 8, in intermediate rock is 8 to 21 and in felsic igneous rock is from 21 to 70, respectively (Hayashi, et al., 1997). Al_2O_3/TiO_2 ratios of all the sandstones (Table 3) in the study areas are 7.0 - 13 in Olambe, 7.6 – 13.2 in Yakoyo and 13.3 – 36.7 in Daniel-1 implying that both Olambe and Yakoyo have input from intermediate igneous rocks and Daniel-1 dominantly felsic igneous rock. The paleotectonic discrimination plot of bivariate SiO_2 against K_2O/Na_2O (Roser and Korsch, 1986) (Figure 11), and La-Th-Sc ternary plot of Jahn and Condie, (1995), (Figure 12), all suggest passive margin continental basement rock as the source of these felsic igneous rock that produced the sandstones.

Some trace elements are enriched than others igneous and metamorphic rocks that serve as progenitor for clastic sedimentary rocks. Chemical compositions of these source rocks can be traced in the resultant clastic rocks.

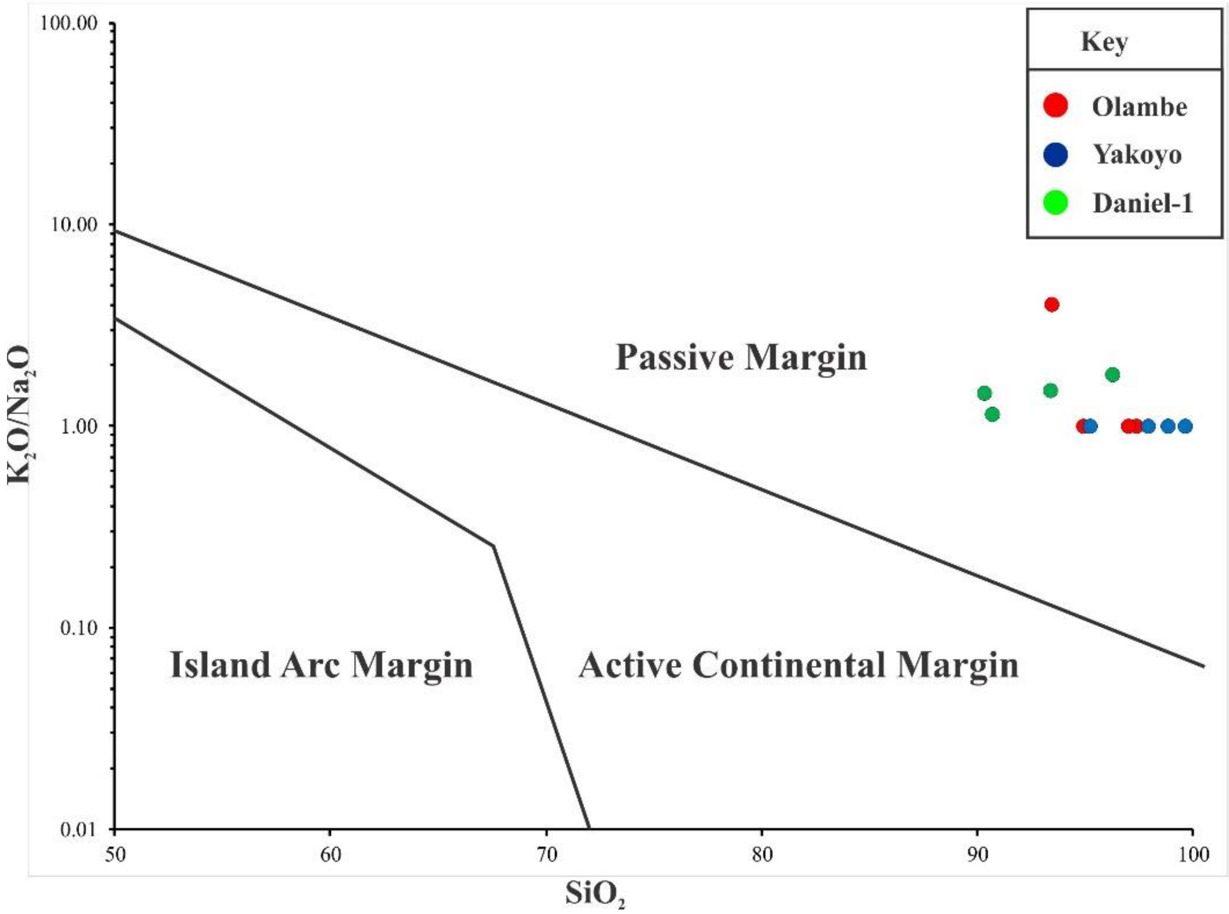

Figure 11: Plot of SiO_2 against K_2O/Na_2O showing paleotectonic discrimination within passive, Island Arc and Active continental margins. The sandstones fall within the passive margin origin. (Modified After Roser and Korsch, 1986)

Ratios of some of this trace elements (Al/Ti, Th/Cr, Th/Co, Th/Sc, and La/Sc) derived from sediments from felsic and mafic rocks compared with the Upper Continental Crust (UCC) have been used in many studies to infer the provenance (Table 6).

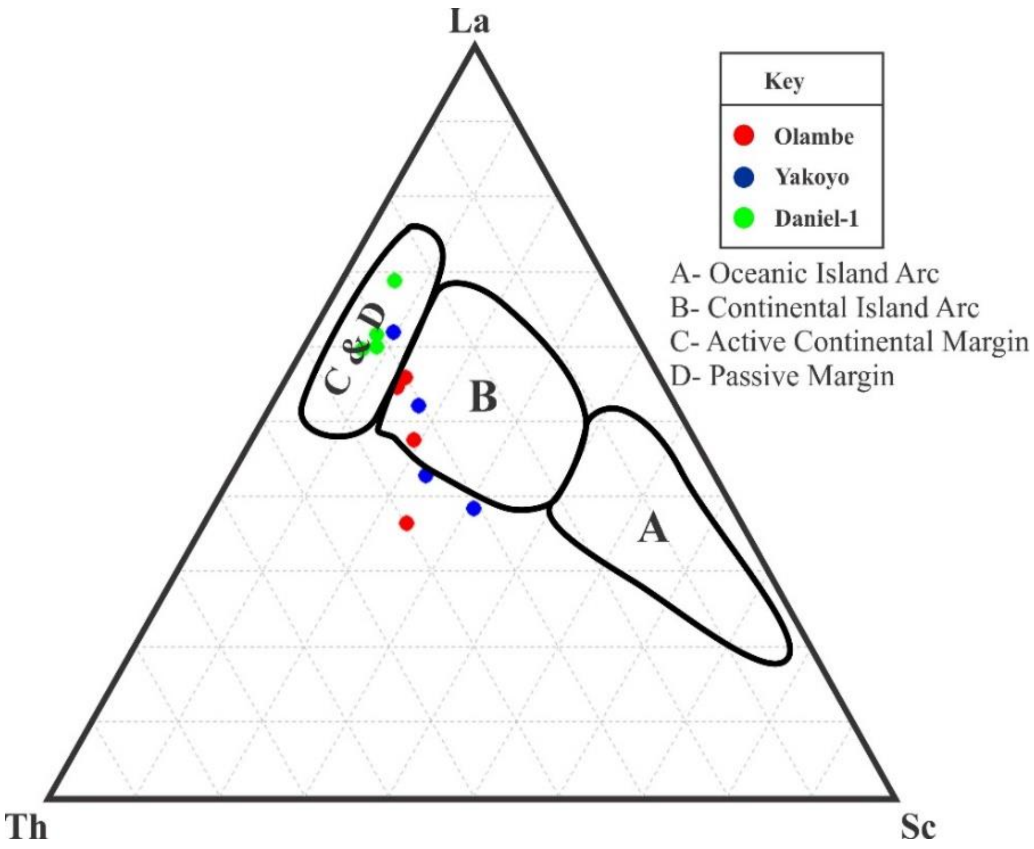

Figure 12: La-Th-Sc ternary plot of the analysed sandstone samples showing Continental, Active continental and Passive Margins dominant of granite and granodiorite rocks (after Jahn and Condie, 1995)

Table 6: Elemental ratio of the studied sandstone samples compared to felsic rocks, mafic rocks and UCC

Ratios	**Studied Sandstones**	**Felsic rocks**	**Mafic rocks**	**Upper Continental Crust**
Al/Ti	7.00 - 36.37	21.00 - 70.00	3.00 - 8.00	30.34
Th/Sc	1.00 - 4.75	0.84 - 20.50	0.05 - 0.22	0.79
Th/Co	1.10 - 12.50	0.67 - 19.40	0.04 - 1.40	0.63
Th/Cr	0.05 - 0.60	0.13 - 2.70	0.018 - 0.046	0.13
La/Sc	1.25 - 11.00	2.5 - 16.30	0.43 - 0.86	2.21

Felsic source rocks are commonly enriched in Aluminum, Thorium and Latium while titanium, chromium, cobalt and scandium more concentrated in mafic rocks (Taylor and McLennan, 1985, Cullers et al., 1988, Hayashi et al., 1997 and Madukwe et al., 2016). The results in Table 6 suggest that though there are some input from mafic source but they are typically from felsic origin coupled with the plot of La/Sc versus Th/Co (Figure 13) that points to more of silicic origin.

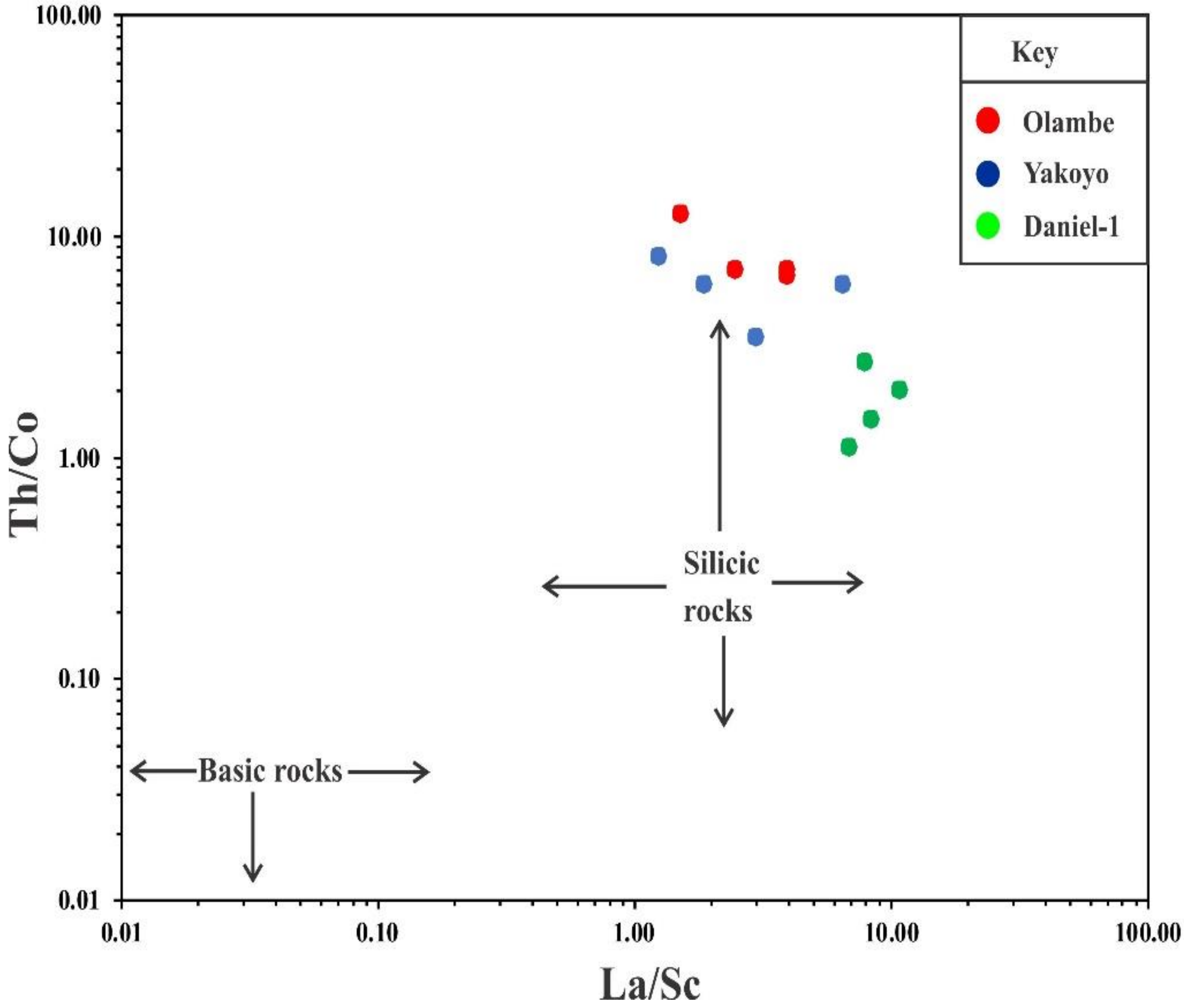

Figure 13: Th/Co versus La/Sc diagram for the sandstone samples (after Cullers, 2000)

5.3. Depositional Environments of the Sandstones

Grain size is very useful in identifying prevailing environments and conditions of clastic sedimentary rocks such as sandstones (Folk and Ward, 1957, Friedman, 1979 and Bui et al., 1990). Grain size data becomes significant when integrated with other relevant sedimentary features. All the sandstones within the aquifers across the study areas have similar textural characteristics confirmed by the fact that they are all very positively skewed. Most of the sandstones are leptokurtic to extremely leptokurtic while others are mesokurtic and platykurtic. Moderate sorting and positive skewness have been used as an indicators of low energy environment characterized by differential deposition with fairly consistent water current typical of fluvial and beach environments (Selley, 1985 and Tucker, 1988).

Plot of sorting (Standard deviation) against mean and Kurtosis versus skewness (Figure 14) of Friedman (1967, 1979), and Ojo, (2012) suggests a predominance of fluvial origin for all the sandstones with some tidal interference.

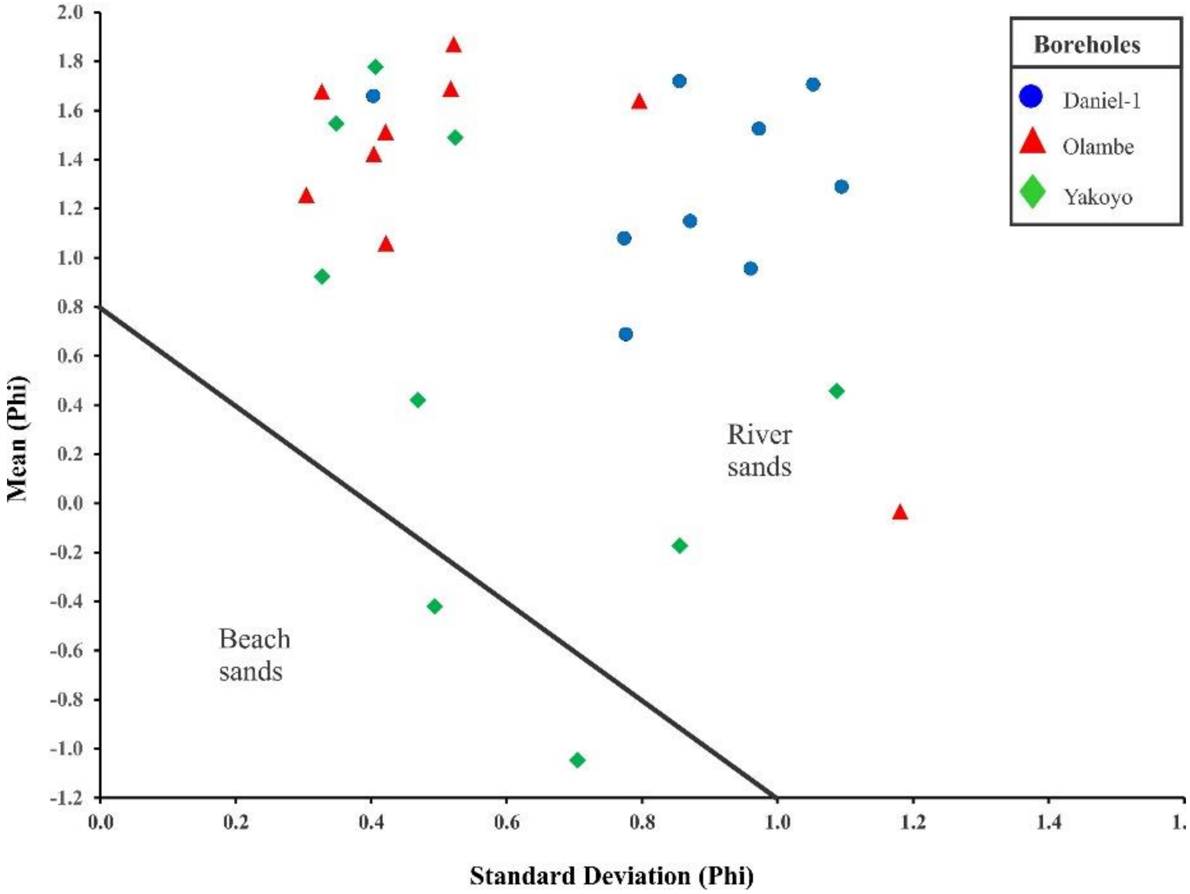

Figure 14: Plot of standard deviation against mean suggesting different depositional agents for the sandstones in the study area.

5.4. Reservoir Potential of the Sandstones

The textural and mineralogical sub-mature to mature nature of the studied sandstones are derived from being medium to coarse grained, moderately to well sorted, and sub-arkose - arenites to quartz arenites features. These attributes are peculiar to a well reworked sandstones exposed to long distance transportation thereby removing the less resistant minerals. The less resistant minerals are dominantly those that produce clay minerals that becomes the matrices or cementing materials that reduces pore spaces and permeability. 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 and Ojo, 2012).

Coarse grained texture preserved porosity better than fine grained because of the packing pattern in the body of the rock. The moderately to well sorted grains also encourages better grain arrangement than the poorly sorted ones under similar environmental conditions. Studied sandstones are loose and not indurated to reduce pore spaces and their connectivity probably because of their shallow depth of about 30 to 40m which is not significant in producing temperature that enhances cementation. The studied sandstones at their current shallow depth may not have significant cementation challenges that is known for reducing permeability quality of sandstones at depth. Mechanical compaction traceable on mineral grains as strain or grain fracturing inherited by the sediment burial (Taylor, 1950; Basu et al., 1975) are not common. More also monocrystalline grains are dominant as against the polycrystalline grain which are products of diagenetic alteration due to compaction. Their chemical composition from various statistical analysis gave further credence to the sandstones as sub-arkose to sublitharente, well reworked and have been transported reasonably far away from the source. These textural and transportation process have enhanced the quality of the sandstones as a good aquifer because of better porosity and permeability in sub-arkose and sublitharenite than the arkosic sandstones.

The textural, mineralogy and chemical attributes of the sandstones in the study areas have a close resemblance to the Turonian-Coniacian sandstones of Afowo as reported in Adeoye et al. (2020) and Adeoye et al., (2022). This Afowo sandstones in Nigerian part of the basin is coarse grained, moderately to well sorted quartz arenite and possess good reservoir qualities at the deep subsurface around the coastline to the offshore from where hydrocarbon is being currently produced. It also extends to onshore northwestern part of the basin where the bitumen deposit within the sandstones is commonly referred to as Tar sand. Likewise, the post-transform Albian and Cenomanian-Maastrichtian marginal marine to turbidite potential clastic reservoir sections (Tucker, 1992 and

Macgregor et al., 2003) of neighbouring Espoir and Belier fields of Cote d'Ivoire and Seme in Benin Basin resemble this probably extends to Aje oil field in Nigeria deep-water of Dahomey Basin where Turonian sand is being targeted for oil production. This sandstone probably has a geographical spread across the basin from the western boundary close to the Niger Delta basin through Benin Republic to the Eastern part of Ghana.

The advent of more subsurface data from core, seismic and well log in the future studies will establish the wide and geographical extent of the Pre-Santonian Afowo sandstones in the eastern Dahomey Basin, Southwestern Nigeria.

6. Conclusions

The grain size, petrography and geochemical studies of the Turonian to Coniacian (TC) sandstones from the three boreholes (Olambe, Yakoyo and Daniel-1) around the northern part of eastern Dahomey Basin, south western Nigeria reveals that:

i. The sandstones are coarse grained, moderately to well sorted, sub-angular to sub-rounded grain indicating exposure to long distance transportation.

ii. The sandstones across the studied region ranges from sub-arkose to quartz-arenites reflecting they are mineralogical and textural sub mature to mature clastic rocks.

iii. They are dominantly deposited in a non-marine fluvial paleoenvironments

iv. Sediments source of supply into the basin are largely from the felsic and passive margin granitic rocks.

v. They have attributes that suggest they are potential reservoir that will effectively allow transmission of fluid.

vi. The studied sandstones resemble the Turonian – Coniacian sandstones in the deep subsurface and are probably geographically well spread across the basin from the Nigeria onshore and offshore to Benin and Eastern part of Ghana.

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