Geochemical Analysis and Sedimentary Characteristics of the Nigerian Tar Sand; Implications on Classification, Maturity and Depositional Environment

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Abstract — 14 subsurface samples from 3 wells (denoted as well A, B, C,) were selected for analysis of geochemical and sedimentary characteristics for the purpose of inferring on sediment classification, maturity and paleo – depositional settings of the Afowo Formation of Dahomey Basin. The study areas are located at Ayede-Ajegunle with coordinate 6.58 N, 4.62 E as Well A, Araromi-Obu/Ago Alaye with coordinate 6.59 N, 4.54 E as Well B and Ajegunle with coordinate 6.60, 4.60 E as Well C. Grain size analysis was carried out, parameters computed for were mean, mode, standard deviation, kurtosis, and skewness. Sediments from Well A range from fine to very fine grained sizes. However, samples between depth 69m and 72m have their grain sizes ranging from medium grained to very fine grained. The grains are moderately sorted to very well sorted, platykurtic to mesokurtic and symmetrically skewed. The grains from Well B range from fine to very fine grain sizes.

The grains are mostly moderately sorted, mesokurtic to very platykurtic and symmetrical to strongly coarse skewed. The result of grain size analysis for core samples from Well C are largely fine grained. The grains are moderately sorted, platykurtic and fine skewed. The sandstones found in wells B and C should be relatively closer to the distal position of the basin and reflect single source of sediment supply (largely unimodal). This is due to the comparatively narrow range of grain size observed. Multivariate analysis shows that the environment of deposition was dominated by fluvial activities.. Major elements analysis result showed higher SiO2 with an average of 69.3%, AlO3 with an average of 12.9% and Fe2O3 with an average of 3.49%.

Relevant crossplots with the oxides were used for classification, maturity index and depositional setting inference. From the crossplot of Log (Fe2O3/K20)/Log (SiO2), 11 of the sediments are classified as Iron Sands while 4 of the samples were classified as Iron Shale. Scatter plot of SiO2/Al2O3+K2O+Na2O shows that climatic conditions at deposition were humid to semi – humid. The chemical index of alteration (CIA) values for the sampled locations ranges from 98.97-99.90 with an average of 98.61 while the chemical index of weathering (CIW) ranges from 98.21-99.89 with an average of 99.53. Observation from the thin section showed that quartz percentage made up 75% with the absence of feldspar and lithic fragment while iron makes up for the rest 25%.

Upon this, the ferruginous sandstones can be said to belong to the class of Quartz Arenites. It is obvious that from the above results that the sediments were of fluvial origin and its source rock was exposed to intensive weathering which depicts matured sediments.

Keywords — geochemical analysis, sedimentary characterstics, tar sand, despositional environment.

INTRODUCTION

The Benin (Dahomey) Basin is one of a series of West African Atlantic Margin basins that originated during the period of rifting in the late Jurassic to early Cretaceous. (Omatsola andAdegoke, 1981; Weber and Daukorou, 1975; Whiteman, 1982).

The basin expanse stretches along the coast of Nigeria, Benin Republic, Togo and Ghana in the margin of the Gulf of Guinea. It is separated from the Niger Delta in the Eastern section by Benin Hinge Line and Okitipupa (Wilson and Williams; 1979; Coker and Ejedawe, 1987, Onuoha, 1999).

The eastern Dahomey basin of the Nigeria sector which is a host to the Tar Sand contains widespread wedge of Cretaceous to recent sediments that builds up towards the offshore about 3000m. The basin has sparked up much geological interest as a result of the occurrences of bitumen, and other industrial minerals (Nton 2001).

Exploration for hydrocarbon commenced in this basin in 1908, near Okitipupa, east of Lagos, where bituminous sands outcrop. The Tar Sand belt stretches to about 120 km by 6 km in Southwestern Nigeria from the Okitipupa ridge/ western edge of the Tertiary Niger Delta to as far west as Ijebu-Ode in Ogun State.

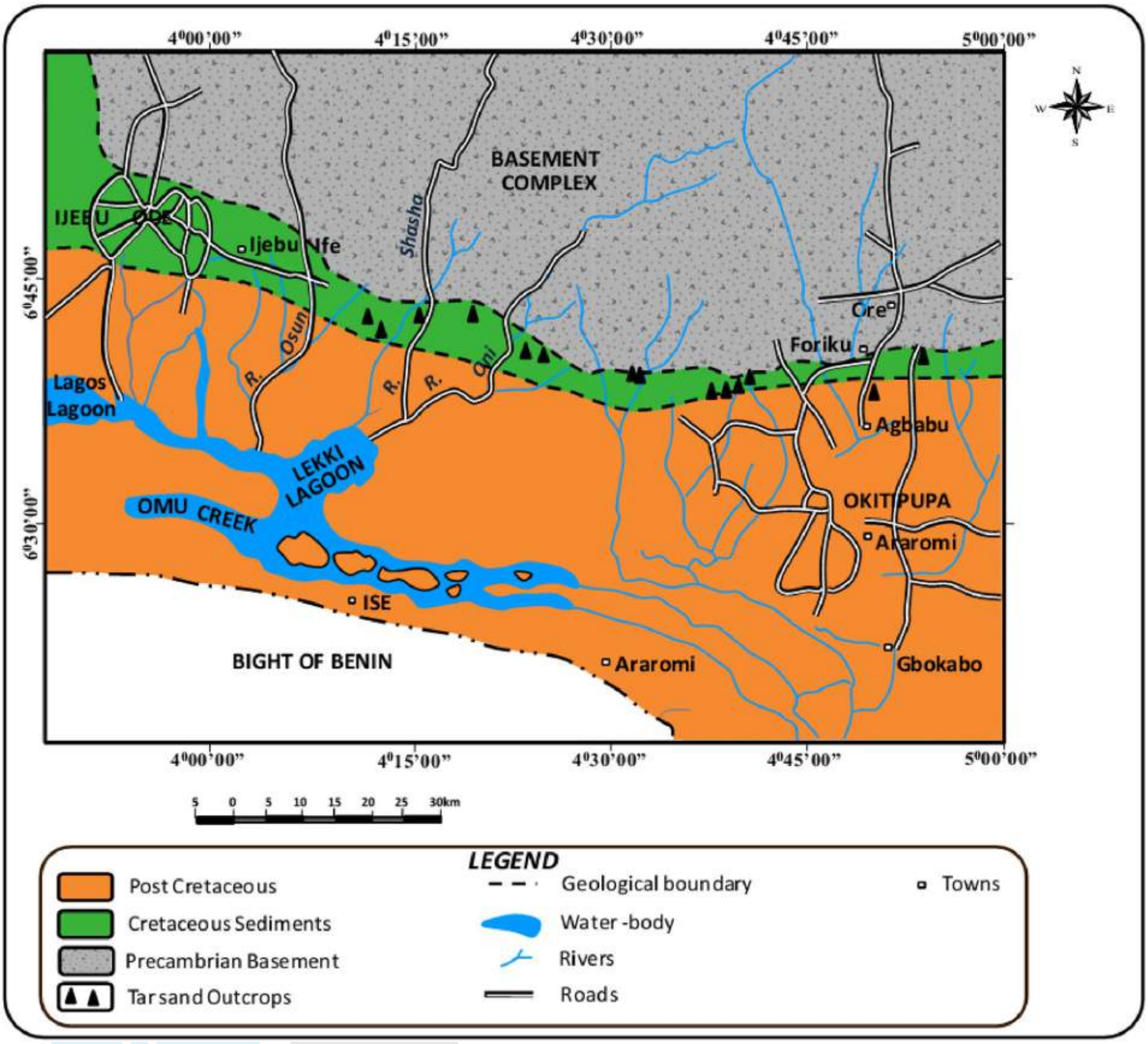


Fig. 1 Generalized geological map of the Eastern Dahomey Basin showing area extent of the tar sand deposits. Modified after Enu (1985)

Extensive work on this heavy oil deposit has been done, ranging from: its geology, oil saturation and its reserve evaluations as well as sedimentary characteristics of the associated sands (Adegoke et al. 1980; Enu 1987).

The physicochemical properties of the resource in relation to production and processing have been studied (Oshinowo et al. 1982; Oluwole et al. 1985). The origin of the bitumen has been discussed (Coker 1990 ;). Enu (1985) delineated two horizons: X (shallow) and Y (deeper). The shallower can be harnessed by open cast mining, and the deeper horizons by steam-assisted gravity drainage.

STUDY AREA

This study sets out to examine the geochemical and sedimentary characteristics of subsurface occurrences of the bituminous sands from 50m down, based on available data. These characteristics will then be applied for sediment classification, infer on sediment maturity (which is key index for basin maturity) and paleo – depositional settings.

The study areas are located at Ayede-Ajegunle with coordinate 6.58 N, 4.62 E, Araromi-Obu/Ago Alaye with coordinate 6.59 N, 4.54 E and Ajegunle with coordinate 6.60, 4.60 E. Samples used for the study were obtained from three cored holes labelled: Wells A, B and C respectively, Fig. 2.

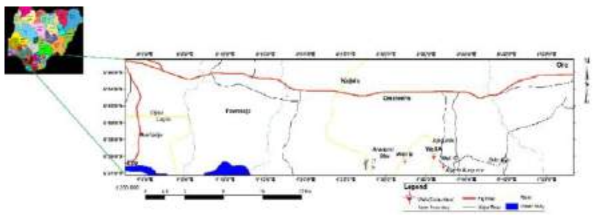


Fig2. Topographic map of study area.

Sedimentary Fill of Dahomey Basin

Studies carried out by Jones and Omatsola and Adegoke (1981), Hockey (1984), and Agagu (1985) who depended on earlier works done by Reyment (1965), shows that in most part of the basin, the stratigraphy is dominated by sand–shale repetitions, with occurrences of limestones and clays.

Research methodology

Fourteen (14) selected core samples were used in this study. The lithological logs of the borehole of each location were produced by logging the core samples. Samples were collected from each lithofacies for laboratory analyses which included: geochemical and grain size and thin section analysis.

	Jones and Hockey (1964)		Omatsola and Adegoke (1981)		Agagu (1985)	
	Age	Formation	Age	Formation	Age	Formation
Quaternary	Recent	Alluvium			Recent	Alluvium
Tertiary	Pleistocene-oligocene	Coastal plain sands	Pleistocene to oligocene	Coastal plain sands	Pleistocene to oligocene	Coastal plain sands
	Eocene	Ilaro	Eocene	Ilaro Oshoshun	Eocene	Ilaro Oshoshun
	Paleocene	Ewekoro	Paleocene	Akinbo Ewekoro	Paleocene	Akinbo Ewekoro
Late Cretaceous	Late Santonian	Abeokuta	Maastrichtian-Neocomian	Araromi-Afowo-Ise	Maastrichtian-Turonian-Neocomian	Araromi Afowo Ise
Precambrian crystalline basement rock						

Fig. 3. Age and stratigraphic relationship of the formations of the Dahomey basin (Adapted and modified by various Authors)

RESULT AND DISCUSSION

Core sample description from the study area

Lithological description of the study area was based on the available core samples collected from the three locations. The columnar lithological descriptions of the studied wells are shown in Figs. 4, 5 and 6.

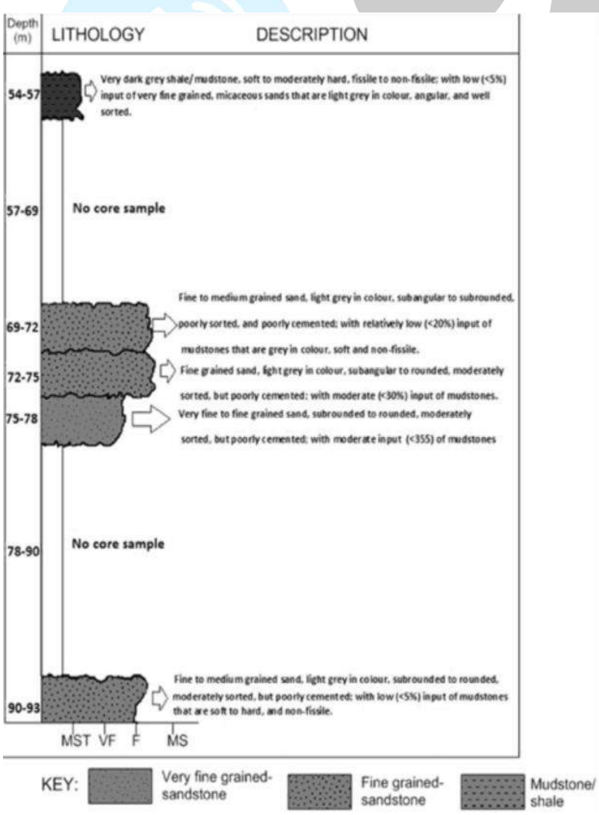


Fig. 4 Log-section of core samples (Well A)

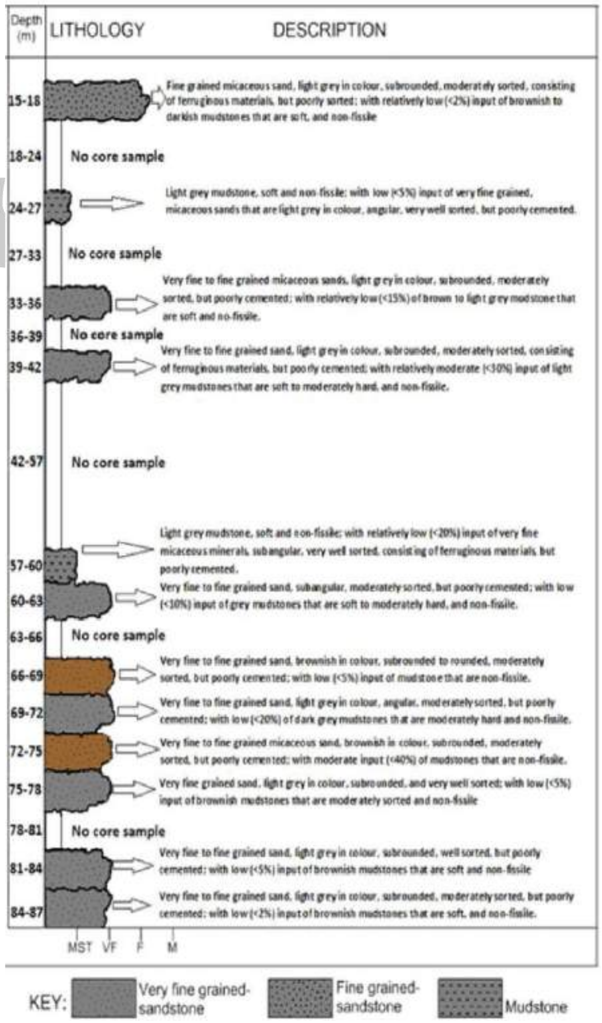


Fig. 5 Log-section of core samples (Well B)

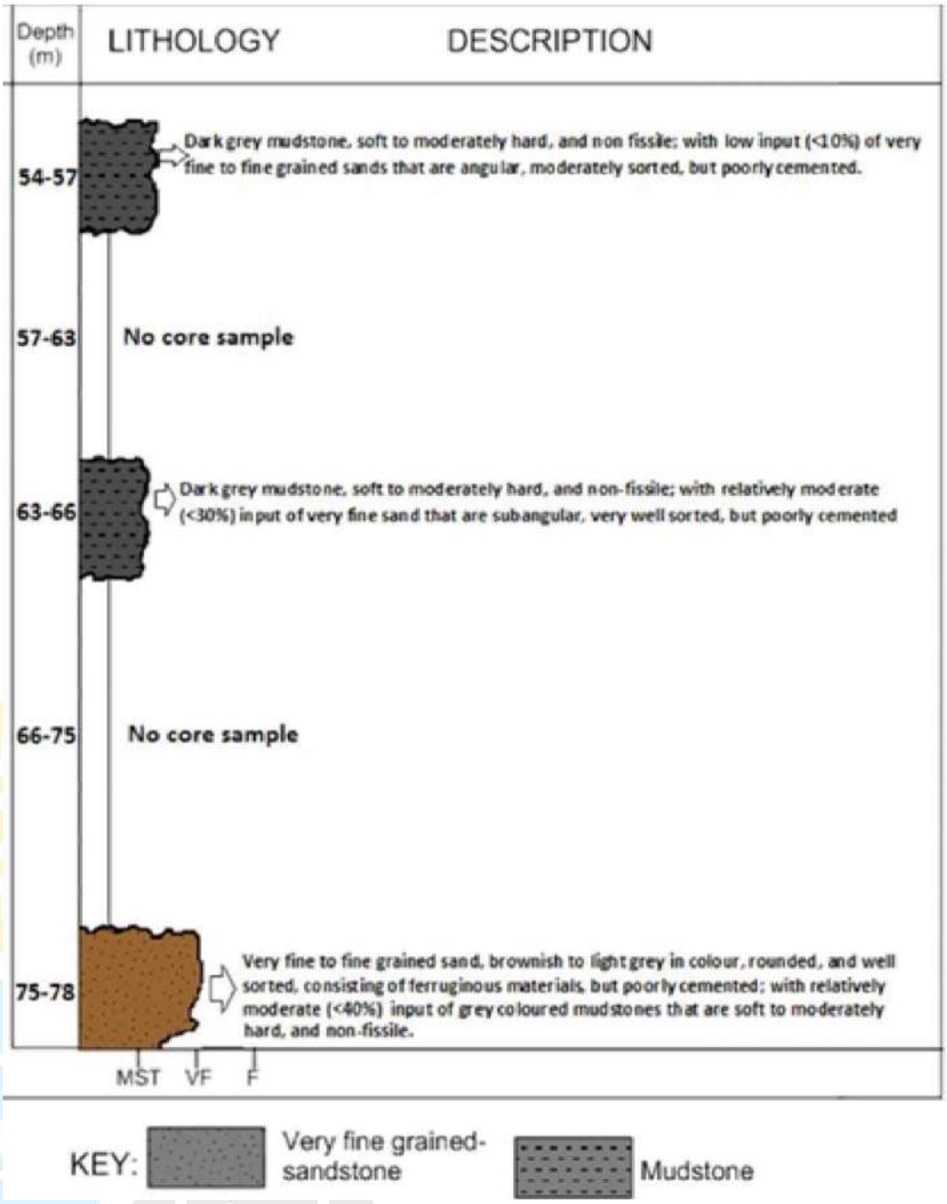


Fig. 6 Log-section of core samples (Well C)

Grain size analysis

Derivatives from parameters such as roundness, sphericity, grain size and sorting, from grain size analysis, are suitable tools to deduce the provenance and transport history of sediments.

The use of grain shape to identify sedimentary environments assumes that grain morphology reveals environmental history (Krinsley and Doornkamp 1973 ;). The results obtained from this analysis carried out on the samples are displayed on table 1.

Table 1 Results of grain size analysis

S/N	Sample No.	Mean	SD	Kurtosis	Skewness	Interpretation
1	Well A (69-72)	2.594	1.039	0.759	− 0.045	Fine sand, poorly sorted, symmetrical, platykurtic
2	72–75	2.891	0.753	0.694	0.098	Fine sand, moderately sorted, symmetrical, platykurtic
3	75-78	2.656	0.936	0.740	0.049	Fine sand, moderately sorted, symmetrical, platykurtic
4	90-93	2.400	1.062	1.054	0.069	Fine sand, poorly sorted, symmetrical, mesokurtic

5	Well B (60-63)	2.971	0.732	0.733	0.040	Fine sand, moderately sorted, symmetrical, platykurtic
6	66-69	3.080	0.974	0.912	0.724	Fine sand, moderately sorted, symmetrical, platykurtic
7	69-72	3.101	0.924	0.844	− 0.703	Very fine sand, moderately sorted, very coarse skewed platykurtic
8	72-75	2.656	0.936	0.740	0.049	Fine sand, moderately sorted, symmetrical, platykurtic
9	75-78	2.512	1.043	1.099	0.019	Fine sand, poorly sorted, symmetrical, mesokurtic
10	81-84	2.640	1.021	0.779	− 0.074	Fine sand, poorly sorted, symmetrical, platykurtic
11	84-87	2.596	0.925	0.771	0.127	Fine sand, moderately sorted, fine skewed, platykurtic
12	Well C(54-57)	2.901	0.680	0.602	0.251	Fine sand, moderately well sorted, fine skewed, very platykurtic
13	(63-66)	2.613	1.056	0.883	− 0.074	Fine sand, poorly sorted, symmetrical, platykurtic
14	(75-78)	2.971	0.732	0.733	0.040	Fine sand, moderately sorted, symmetrical, platykurtic
AVE		2.745067	0.915214	0.810214	0.127615	

Interpretations from grain size analysis

Data obtained from lithological description and grain size analysis confirmed that the core samples from well A (Ayede-Ajegunle) range from fine to very fine grained sizes (Fig. 6). However, samples between depth 69m and 72m have their grain sizes ranging from medium grained to very fine grained. The grains are moderately sorted to very well sorted, platykurtic to mesokurtic and symmetrically skewed. The particle size for core samples from Well B (Araromi-Obu/ Ago-Alaye) range from fine to very fine grain sizes. The grains are mostly moderately sorted, mesokurtic to very platykurtic and symmetrical to strongly coarse skewed. The result of grain size analysis for core samples from Well C (Ajegunle A4) are largely fine grained. The grains are moderately sorted, platykurtic and fine skewed. The sandstones found in wells B and C should be relatively closer to the distal position of the basin and reflect single source of sediment supply (largely unimodal). This is due to the comparatively narrow range of grain size observed.

Multivariate Analysis

According to Sahu (1964), using the statistical method of analysis of the sediments to interpret the variations in the energy and fluidity factors seems to have excellent correlation with the different processes and the environment of deposition. Multivariate analysis of the sediment samples was carried out using the following equation:

Shallow Marine/ Fluvial

$Y_U = 0.2852M-(8.7604(SD)^2)-4.8932SK+0.0482KU$

If $Y \geq 7.4190$ environment is shallow Marine

If $Y \leq 7.4190$ environment is Fluvial

M- Mean

SD- Standard Deviation (Sorting)

Sk- Skewness

Ku- Kurtosis

$Y_U = 0.2852M-(8.7604(SD)^2)-4.8932SK+0.0482KU$

$Y_U = 0.2852(2.745067)-(8.7604*0.837617)-4.8932*0.127615+0.0482*0.810214$

$Y_U = 0.782893-7.33785-0.62445+0.039052$

$Y_U = -7.140355.$

Multivariate analysis shows that the environment of deposition was dominated by fluvial activities. Thus, it can be inferred that the sediments are of fluvial origin.

Geochemical Analysis

Core samples recovered from boreholes were analyzed for major oxide geochemistry. As shown in Table 4.7b, $\mathbf{SiO_2}$ was found ranging from (51.44-84.47) %, with an average of 69.63%, $\mathbf{Al_2O_3}$ ranges from (7.23-24.9) % with an average of 12.49%, $\mathbf{Fe_2O_3}$ ranges from (1.63-

6.26)% with an average of 3.49%, **MgO** ranges from (0.03-0.04) % with an average of 0.032%, **CaO** ranges from (0.01-0.15) % with an average of 0.04%, **Na^2O** ranges from (0.01-0.02)% with an average of 0.015%. **K_2O** ranges from (0.019-0.19) % with an average of 0.11%, **TiO_2** ranges from (0.74-1.65) % with an average of 1.02%, **MnO** ranges from (0.01-0.01) % with an average of 0.01%. The relatively high Al_2O_3 values accounts for lithic fragment content. According to Cingolani et al 2003, chemical alteration of rock during weathering, can lead to depletion of akalis and alkaline earth element and preferential enrichment of Al_2O_3 while low values of the other oxides may be attributed to chemical destruction under oxidizing conditions during weathering and digenesis.

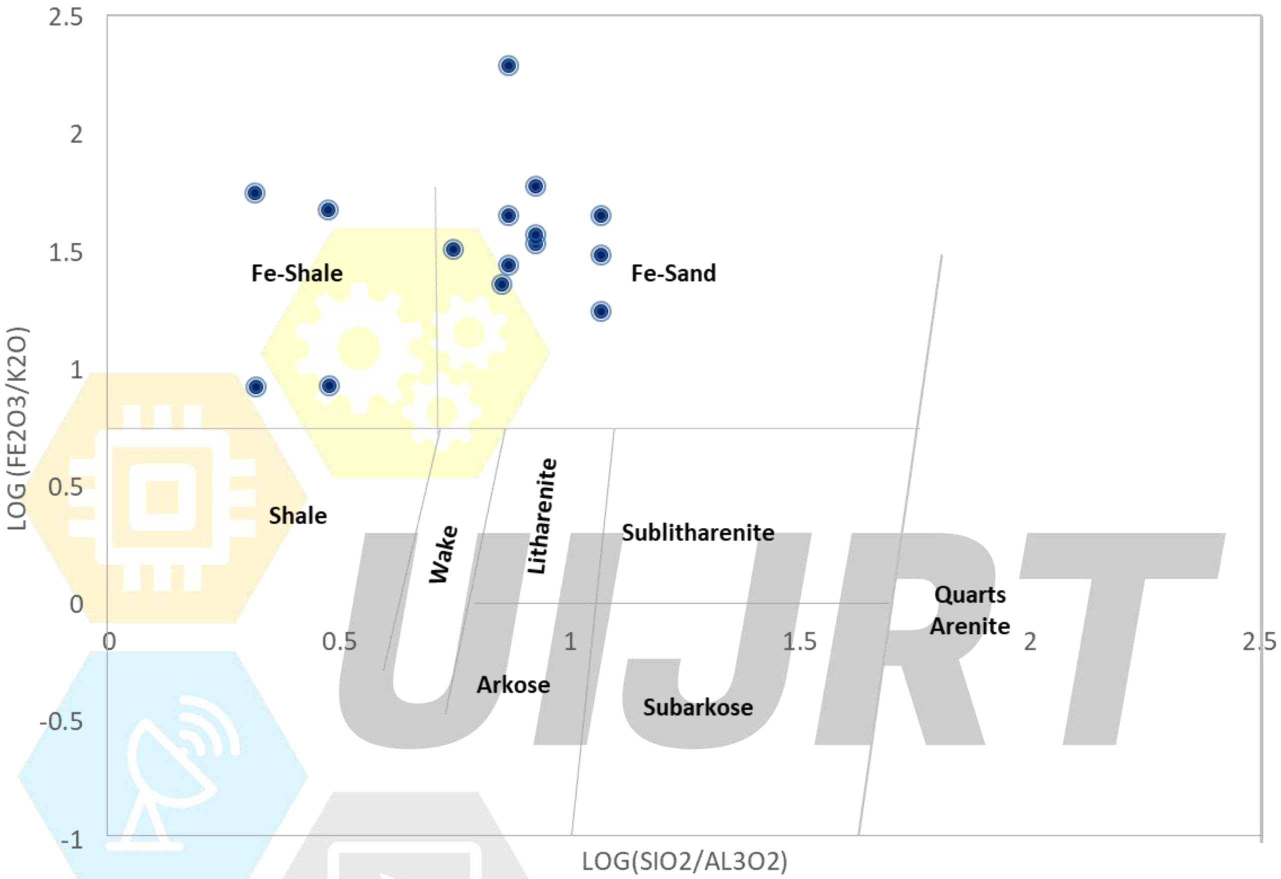


Fig 7 Sandclass system of classification for well samples. Log (Fe_2O_3/K_20)/Log (SiO_2) after Herron 1988

From figure 6 which is the scatter plot for the well samples, it can be observed that out of 14 samples analyzed for major element that 4 plotted in Fe-Shale field while 10 plotted in Fe-sand field. This points out the significant Fe content of the samples. Generally, the samples are classified as Fe – Sands based on Herron's Sand class geochemical classification for terreginous sediments.

Source area weathering

According to Nesbitt and young 1986, previous work done on clastic sedimentary rocks show that their chemical composition is mainly dependent on the weathering conditions at their source rock area. According to them, evaluation of the degree of chemical weathering and alteration can be determined by calculating the Chemical Index of Alteration which is defined as; CIA= ($Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$). This works well when Ca, Na, and K decreases with weathering intensity. Chemical Index of weathering (CIW) proposed by Harnois 1988, is similar to CIA except for the exclusion of K2O in the equation and it's defined as (Al_2O_3/ ($Al_2O_3+CaO+Na_2O$).

Both indices are interpreted similarly with value of 50 representing unweathered upper continental crust while values of roughly 100 depicts highly weathered materials. Low CIA values (50 or less) might also reflect cool and/ or arid conditions (Fedo et al 1995). The CIA values for the sampled locations ranges from 98.97-99.90 with an average of 98.61 while the CIW ranges from 98.21-99.89 with an average of 99.53. It is obvious that from the above results that the source rock was exposed to intensive weathering

Maturity and Climatic Condition during Sedimentation

SiO_2/Al_2O_3 ratios of clastic rocks are sensitive to sediment recycling and weathering processes and can be used as an indicator of sediment maturity. With increasing sediment maturity, quarts survive preferentially to feldspars, mafic minerals and lithics. (Roser and Korsch, 1986). Average ratios of SiO_2/Al_2O_3 for unaltered igneous rock ranges from 3 (basic) - 5(acidic). Values of SiO_2/Al_2O_3 >5 in sandstones are an indication of progressive maturity (Roser et al 1996). From the result of the analysis, the ratio of SiO_2/Al_3O_2 ranges from (2.07-11.66) with an average of 7.10. In this case the high value of SiO_2/Al_2O_3 ratio indicates high maturity and low clayness. According to (Prothero 2004), sandstone usually contains clay minerals growing on its grain surface or in the pore spaces. An approach towards investigating detrital mineralogy has been proposed by (Cox et al 1995; Madueke et al 2014). This is the Index of Compositional Variability (ICV) which is defined as: $(Fe_2O_3+Na_2O+CaO+MgO+TiO_2)/Al_2O_3$. More matured sandstones display lower ICV values less than 1.0 and those sandstones are derived from cratonic environment. While those with values greater than 1 are immature mineralogically. From the result of the analysis the core samples have ICV values ranging from (0.10-0.66) with an average of 0.43. Thus the sediments are mineralogicaly matured this is supported by relative silicate oxide dominance.

Scatter plot of $SiO_2/Al_2O_3+K_2O+Na_2O$ has been used by Suttner and Dutta, 1986 to interpret climatic condition during sedimentation. This discriminates between humid, semi – humid semi-arid and arid climatic conditions. This could also be an index to further infer on degree of chemical maturity. From the scatter plot figure 8 all the samples plotted within humid and semi humid section but one on the arid region. The more humid the weather condition the more chemical reactivity is expected. This is because water will act as a catalyst to leach out labile or less stable chemicals like the Na_2O and K_2O components thus making the more stable chemicals like SiO_2 relatively higher. This can serve as an index for both chemical and mineralogical maturity of sediments.

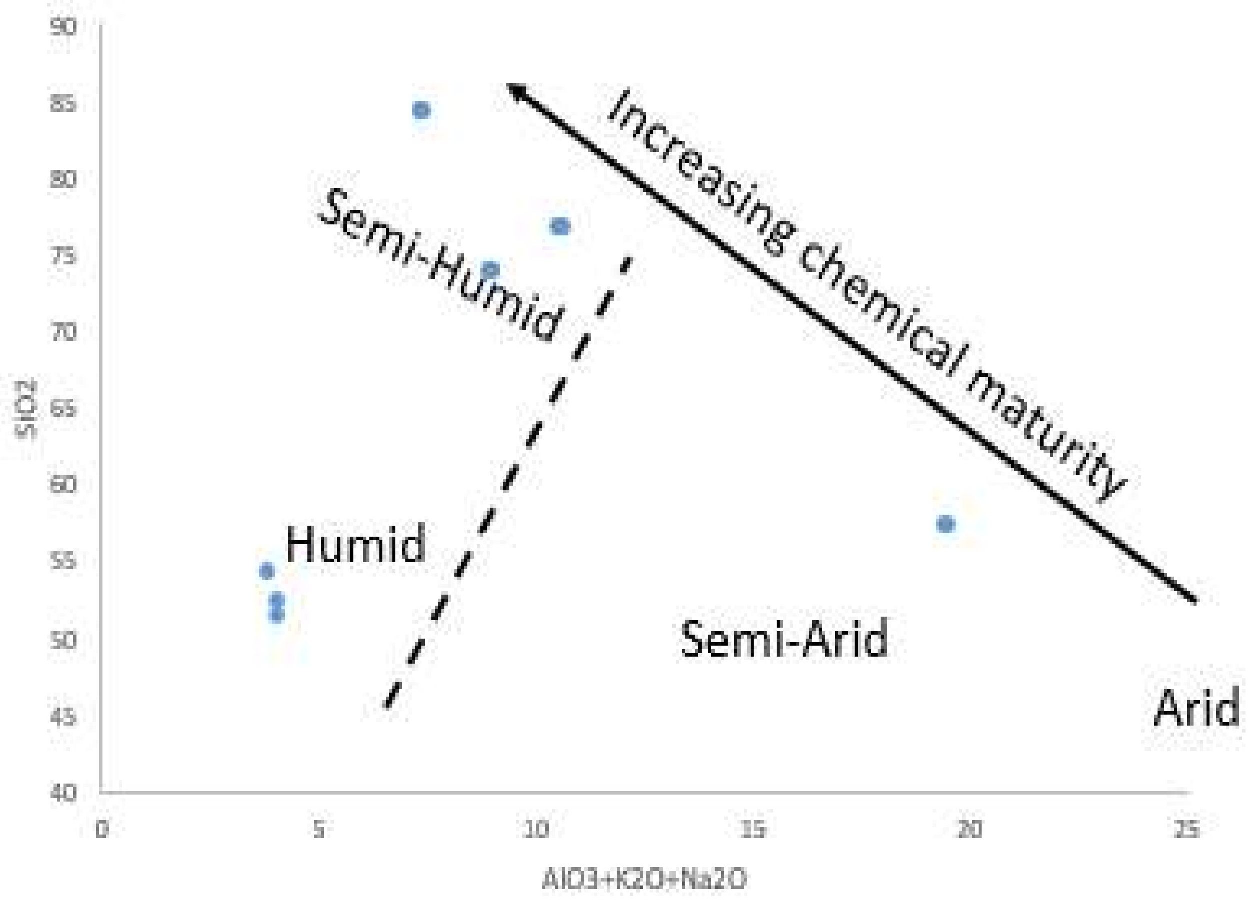
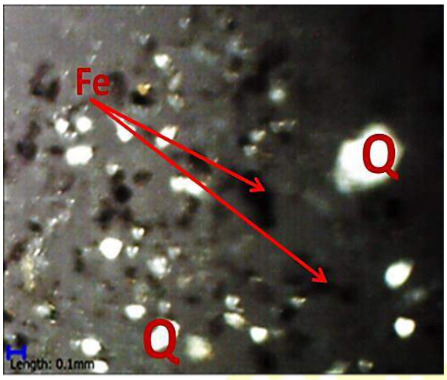
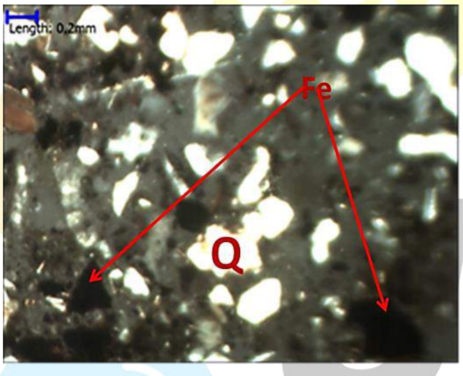


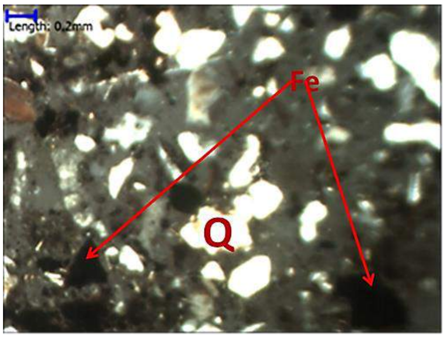
Figure 8 Scatter plot of $SiO_2/Al_2O_3+K_2O+Na_2O$ showing climatic condition during sedimentation.

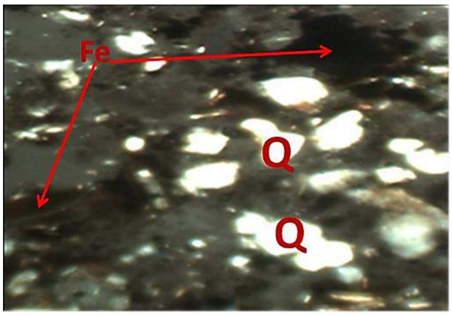
Thin section petrography

Observation from the thin section showed that quartz percentage made up 75% with the absence of feldspar and lithic fragment while iron makes up for the rest 25%. Upon this, the ferruginous sandstones can be said to belong to the class of Quartz Arenites.









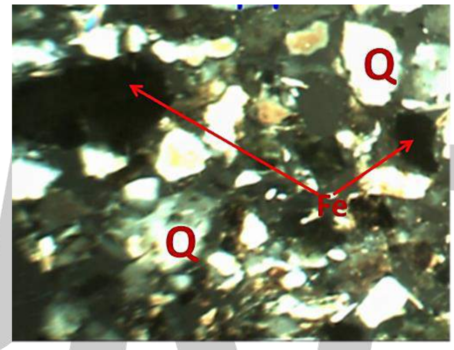


Figure 9a – 9f. Thin section petrography.

Table 2 Modal analysis from thin section for subsurface samples

Mineral	*Modal Analysis (%) for Slide 1*	*Modal Analysis (%) for Slide 2*	*Modal Analysis (%) for Slide 3*	*Modal Analysis (%) for Slide 4*	*Modal Analysis (%) for Slide 5*	*Modal Analysis (%)for Slide 6*
Quarts	50	70	70	75	65	60
Fe-Iron Mineral (Hematite)	50	30	30	25	35	40
Others	Nil	Nil	Nil	Nil	Nil	Nil

CONCLUSION

Geochemical and sedimentary characteristic derivatives has proven a veritable tool in sediment classification, maturity and depositional environment prediction. 14 subsurface samples from the Afowow Formation were subjected to geochemical analysis and sedimentary characterization, from relevant geochemical cross plots, the sediments were classified as iron sands after Heron 1998. This is due to abundant quarts and iron content which are depicted by high content of SiO2 and Fe2O3 respectively. Result from index of compositional variability (ICV) which is a method in investigating sediment mineralogical maturity showed that the sediments are matured. Inference was made on climatic condition during deposition, the sediments were deposited under humid and semi humid conditions. This ensures chemical stability of sediments as all the unstable elements would have been leached away by water. The high values of chemical index of alteration (CIA) and chemical index of weathering (CIW) showed that the sediment were exposed to intensive degree of weathering at source area. Observation from the thin section showed that quartz percentage made up 75% with the absence of feldspar and lithic fragment while iron makes up for the rest 25%. Upon this, the ferruginous sandstones can be said to belong to the class of Quartz Arenites.

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