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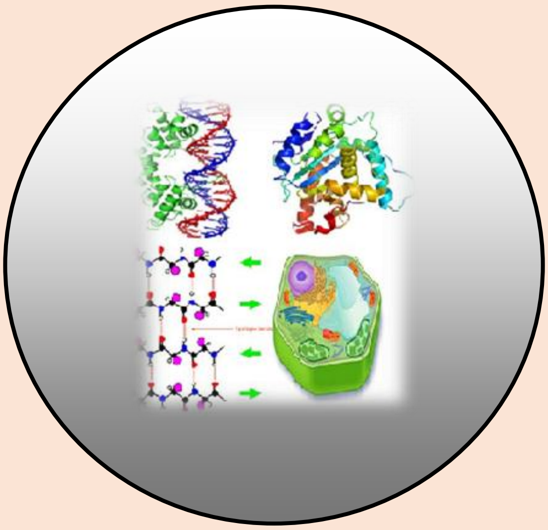

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RESEARCH PAPER

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Petrology and Geochemical Fingerprints of Aspects of Cretaceous Clastic Sediments of Abeokuta Group, Eastern Dahomey Basin Nigeria

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ABSTRACT

A total of 116 core samples from two wells (Ajebandele and Araromi) with coordinates N 060^0 38" 548' and E 040^0 27" 061' and 06^0 38" 020' and E 004^0 27" 594' and depths of 150m and 142 m respectively penetrating Abeokuta Group of the Eastern Dahomey Basin were used for this study. The samples were subjected to thin-section petrography, heavy mineral and inorganic geochemical analysis using Lithium metaborate/tetraborate fusion inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma Electron Spectrometry (ICP-ES). The sandstones revealed dominance of quartz thus were classified as quartz arenites to sublitharenites and subarkoses derived from recycled orogen and continental arc provinces. Limestones in the study area are bioclasts and point to deposition within shallow-marine setting. The presence of heavy mineral suite comprising tourmaline, zircon, rutile, hornblende, garnet, staurolite, apatite, epidote, kyanite, and sillimanite indicates sediments from mixed environments of igneous, dynamo-thermal metamorphic rocks, and reworked sedimentary rocks while Zircon-Tourmaline-Rutile indices of between 66-74% indicates that they are mineralogically mature. The geochemistry revealed average values consistent with intermediate igneous, felsic igneous, and quartzose sedimentary provenances and deposited in an oxic shallow-marine environments. The Chemical Index of Alteration, Plagioclase Index of Alteration and Chemical Index of Weathering have high significant with weathering at the source. Ternary plots of major and trace elements also suggest continental island arc to passive margin settings with preserved signatures of a recycled provenance. The negative europium anomaly from chondrite-normalised Rare Earth Elements patterns, flat Heavy Rare Earth Elements and enriched Light Rare Earth Elements indicate that the Abeokuta Group sediments are derived from felsic source rocks corroborating interpretations from other analyses.
Keywords: Abeokuta Group, Inorganic geochemical fingerprints, Rare earth elements and Weathering indices.

INTRODUCTION

The Precambrian domain of West Africa accommodates important Phanerozoic depositional sites. Among which is the Dahomey Basin, a coastal sedimentary basin covering much of the continental margin of the Gulf of Guinea. It extends from the Volta Delta in Ghana in the west to the Okitipupa ridge in Nigeria in the east. It is a marginal pull-apart basin (Klemme, 1975) or marginal sag basin (Kingston et al., 1983). It developed in the Mesozoic during the separation of African and South American lithospheric plates (Burke et al., 1971; Whiteman, 1982).The basin contains roughly 3000 meters extensive wedge of Cretaceous to Recent sediments, which thicken from the onshore margin (where the predominantly clastic Cretaceous sediments rest on the basement) to the offshore where thick fine-grained, Cenozoic sediments cover the basin floor (Whiteman 1982). The geology, stratigraphy, sedimentology and organic geochemical studies of different parts of the basin have been reported in the literature (Slanky, 1962; Jones and Hockey, 1964; Fayose, 1970; Adegoke, 1980; Omatsola and Adegoke, 1981; Coker et al; 1983; Nwachukwu and Adedayo, 1987; Ekwezor and Nwachukwu, 1989; Ekwezor, 1990; Mosunmolu Nig. Ltd, 1991; Billman, 1992, Idowu et al., 1993; Nton, 2001, Adeigbe and Oyekola, 2019).

The stratigraphic description of sediments in the Eastern Dahomey Basin have been presented by Fayose (1970); Jones and Hockey (1964); Ogbe (1972); Omatsola and Adegoke (1981); Nwachukwu et al., (1992); and Nton (2001) among others (Table 1).

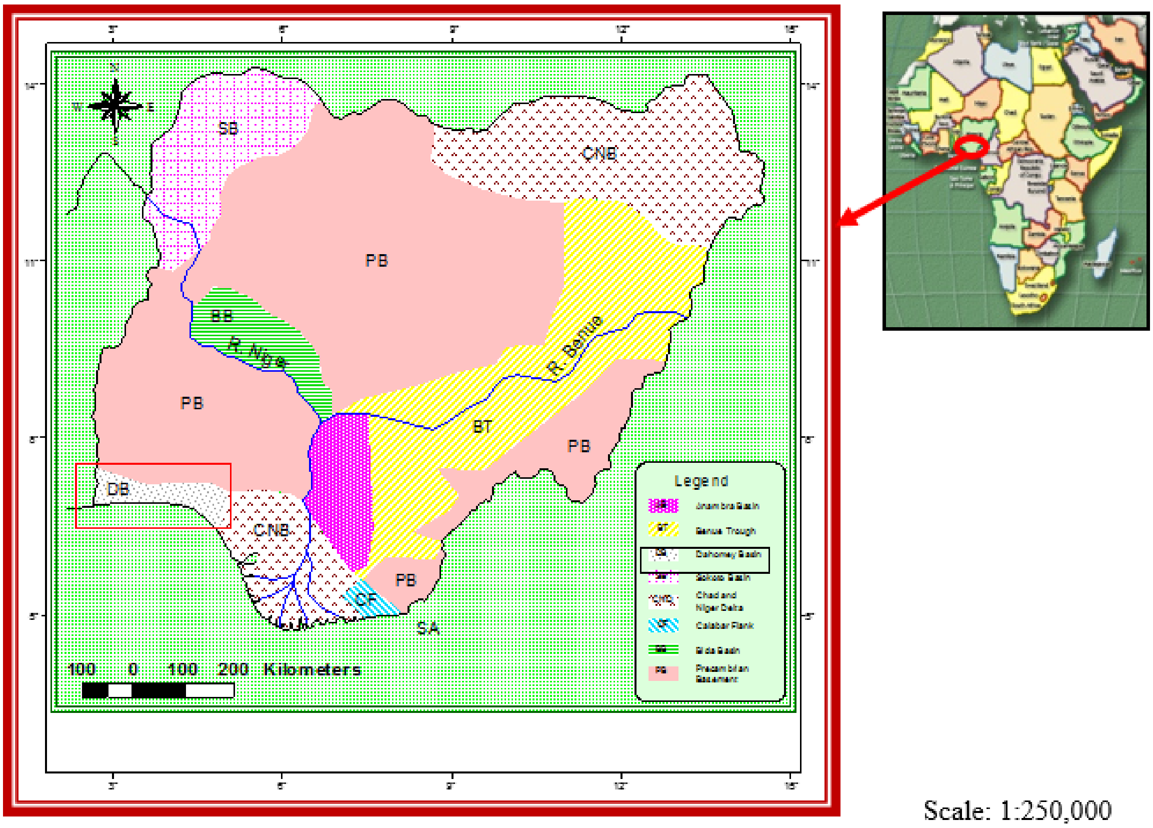


Figure 1. Nigerian Basins with special reference to the Dahomey Basin (modified after Obaje, 2004)

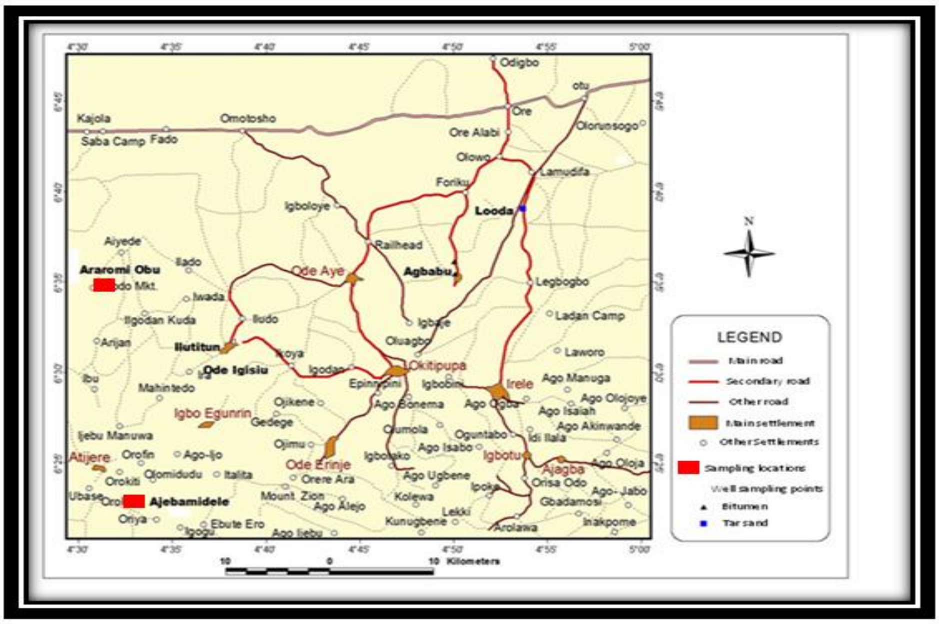
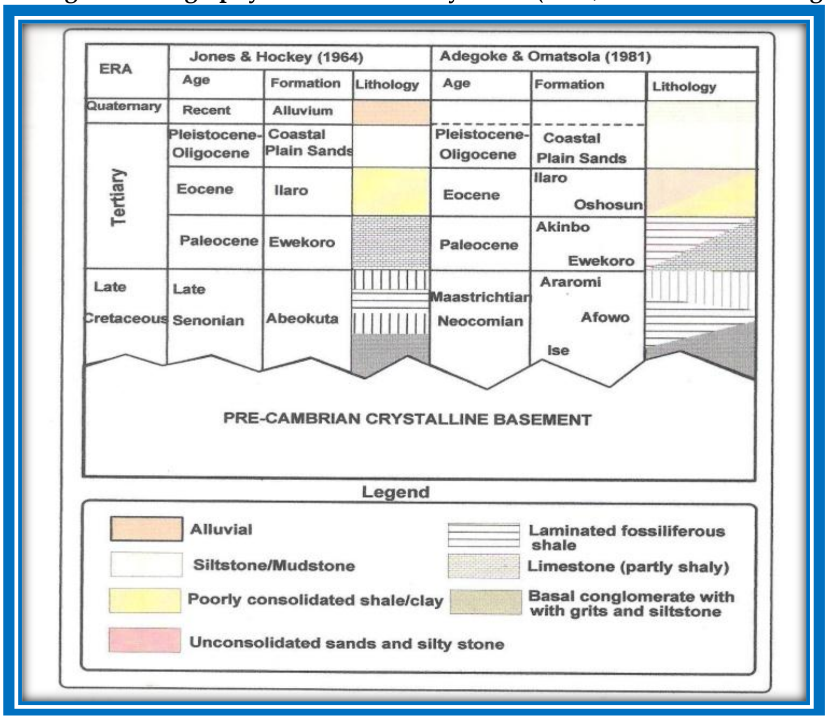


Figure 2. Topographical Map of Nigeria showing wells location points.

Table 1. Showing the Stratigraphy Eastern Dahomey Basin (after, Omatsola and Adegoke, 1981).



MATERIALS AND METHODS

A total of 116 representative core samples done at 3 meter depth interval from Ajebandele and Araromi (Abeokuta Group) were used for this study. The studies include petrography, heavy mineral studies and geochemistry using ICP-AES/MS. The slides were prepared following the normal procedure in the Department of Geology, University of Ibadan thin section laboratory. The samples were thin-sectioned directly while few loose samples were impregnated in epoxy before cutting and mounting on slides for examination by the petrographic microscope. Around 400-500 point counts per thin-section slide were made using the Gazzi-Dickson point counting method as described by Ingersoll et al., (1984), from where their modal composition were calculated. Same goes for the heavy mineral analysis using standard procedure of Bromoform (∂= 2.89 g.cm^{-3}) separation and subsequently examined under petrographic microscope through their optical properties to obtain the complete heavy minerals fraction using grain count method (Mange and Maurer, 1992). The observed heavy mineral assemblages were documented and the ZRT index calculated. Altogether forty samples from the study wells were analysed for major, trace and rare-earth elements at Acme Laboratories Limited Vancouver, Canada using standard procedure of Lithium metaborate/tetraborate fusion using Inductively Coupled Plasma Electron Spectrometry (ICP-ES) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

RESULTS AND DISCUSSION

Lithology Description

The sediments of both wells (Araromi and Ajebandele) showed lithologic homogeneity except with slight variations down the hole. The top of both wells were basically composed of detrital and alluvial deposits of clayey sand and mudstone which was followed by intercalations of shale and sandstones, although, Araromi well had more intervals of shale than sandstone which occurred towards the basal section. Other lithologies observed include siltstone, limestone, sandy clay as well as thin-lenses of coal. Megascopically, the sandstones are fine to medium grained, well sorted and somewhat sub-angular to sub-rounded, while the shales are organic ranging from light grey to black. Majority of the shale samples were very fissile while, others were highly indurated with laminations and specs of mica. The coals are black in colour and could represent sub-bituminous to bituminous coal. The siltstones are very fine to fine grained and very well sorted possessing a milky appearance. It is also worthy of note that some of the sandstone samples appear reddish brown in colour as a result of ferruginisation. Observed limestone samples were fossiliferous with some of the fossil fragments visible to the naked eye.

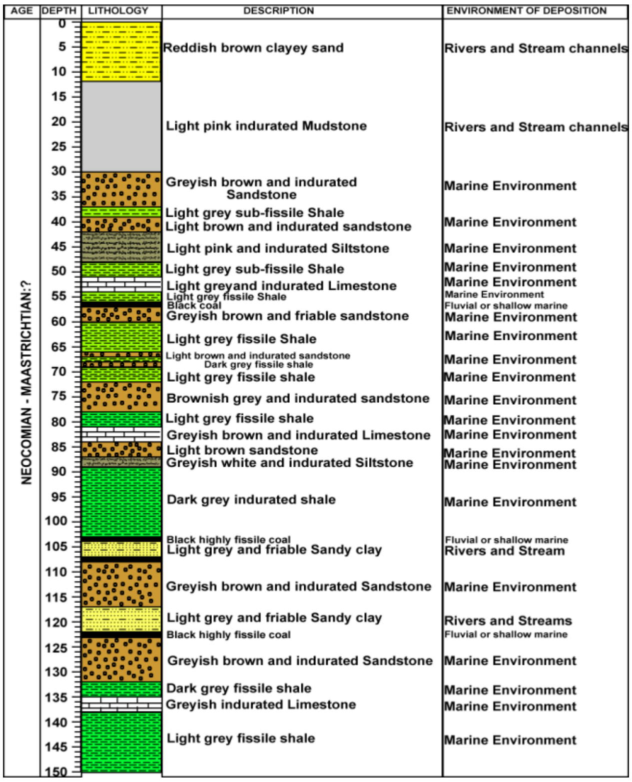


Figure 3. Litho-section of Ajebandele Well.

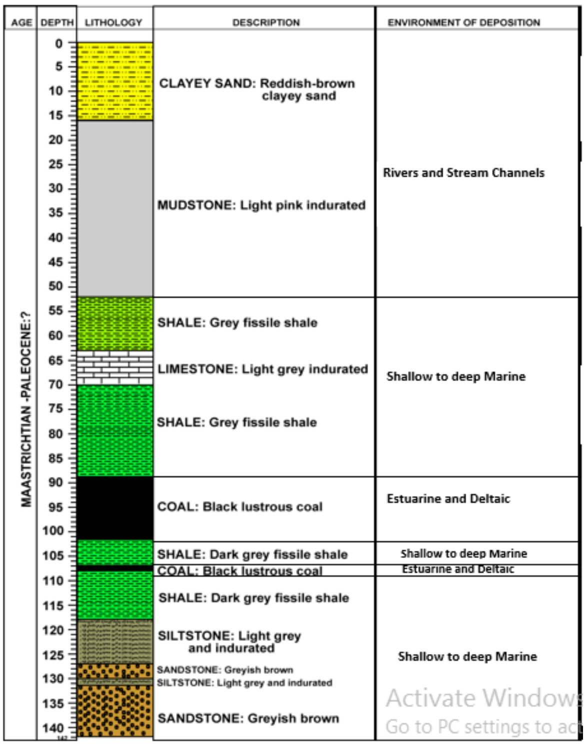


Figure 4. Litho-section showing Araromi Well.

Petrography

Petrography results show that both Ajebandele and Araromi sandstones, Abeokuta Group is rich in quartz, followed by feldspar and lithic fragments. Quartz being the most abundant framework grain makes-up about 86-90%, sub-angular to sub-rounded with few attaining near-rounded shape but nearly equant grains.

They also occur as mono-crystalline and polycrystalline crystals. Their contacts are mostly straight to sutured and very distinct (Figs 5a, b, c, d). Feldspars constitute about 7.3% and are basically the alkali feldspars (microcline). They exhibit a cloudy appearance and brown coloration due to chemical alteration and shows relics of twinning. Next are the lithic fragments which constitute about 6.11% by composition of the sandstones. They mostly occur as low-grade sedimentary lithics in form of chert and shale and low-grade metamorphic lithics in form of quartz-mica-schist. They appear as large crystals and are sub-angular to sub-rounded. They are embedded in a kaolinite matrix and the cementing material is likely calcite and iron-oxide.

The sandstones have dominantly quartzolithic composition of about 86-90% quartz suggesting that they are texturally and chemically mature (Figure 7) (Folk, 1951). It also suggests that the sediments have travelled quite a distance owing to the sub-rounded to rounded grains. Also, the percentage of feldspars and lithic fragments which have been chemically altered corroborated this (Figs. 5a, b, c, d). The occurrence of excessively weathered feldspars points to low source relief and slow sedimentation rate for the sediments. Tucker (1988), discussed that under hot and humid climatic conditions, feldspar weathers to clay minerals and this could also explain why the feldspars and lithic fragments are depleted in the samples. The ternary diagram (Figs. 8 and 9) after Suttner et al., (1981) also explains this theory. The maturity indices of the sandstones ranged from 10.1-32.3 with a mean value of 17.9, this shows that the sandstones are mature (Nwajide and Reijers, 1996). The dominance of the polycrystalline quartz grains is typical of a metamorphic source rock (Pettijohn et al., 1972; Blatt et al., 1972), however, the non-opaque heavy mineral assemblage of zircon, tourmaline, apatite, rutile, stauorolite, garnet, sillimanite, hornblende, and epidote observed for both wells point to mixed environments of acid-igneous rocks, dynamo-thermal metamorphic and sedimentary rocks (Feo-codecido, 1956). The opaque species are haematite, ilmenite and pyrite. The calculated ZTR index for Ajebandele well sediments range from 55-80% with an average of 66.52% and 56-80% for Araromi with an average of 73.79% with the ultra-stable population increasing in the order of abundance from zircon, rutile and tourmaline (Figure 6a-6e). This range indicates that the sediments are also mineralogically mature. This is as a result of intense weathering both at the source and during transportation. The implication is that the sandstone of Ajebandele and Araromi are mature (Hubert, 1962). The limestones components of the wells are all bioclasts containing broken remains of organisms such as bivalves, gastropods and shell fragments. The presence of such organisms indicate shallow-marine environment. However, the presence of abundance quartz with highly weathered feldspars may indicate fluvial environments of medium to high energy levels. The presence of intraclasts also suggests that the sediments have been re-worked owing to the broken fragments of organism's hard part.

Furthermore, the ternary plots of QFL (Fig. 6) classified the sandstones as dominantly quartz arenites with a few plotting in the sublitharenite field, which agrees with the petrography.

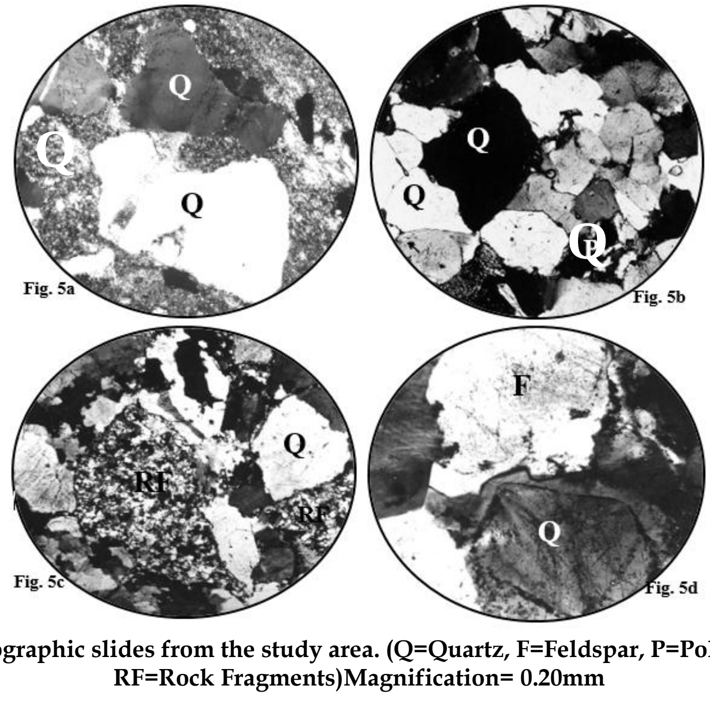


Figure 5a - 5d. Petrographic slides from the study area. (Q=Quartz, F=Feldspar, P=Polycrystalline Quartz, RF=Rock Fragments)Magnification= 0.20mm

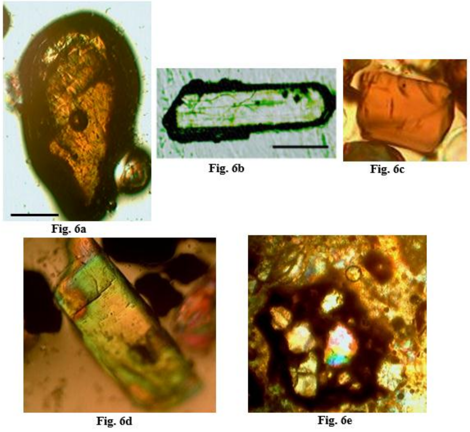


Figure 6. Assemblage of Heavy minerals from the study area (a=Rutile, b=Zircon, c=Tourmaline, d-Hornblende e-Intraclasts) .Magnification = 0.4mm.

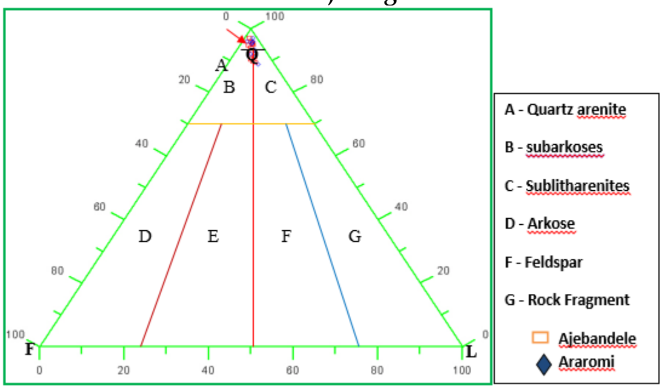


Figure 7. QFL diagram for the sediments of the study area (classification scheme after Folks, 1968).

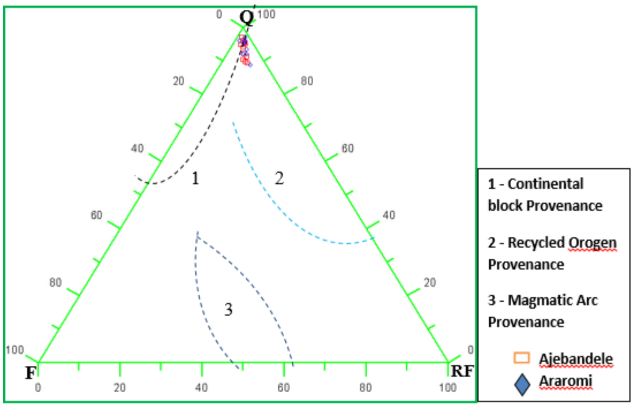


Figure 8. Paleotectonic setting of the analyzed sediments of the study area (After Dickinson and Suczek, 1979).

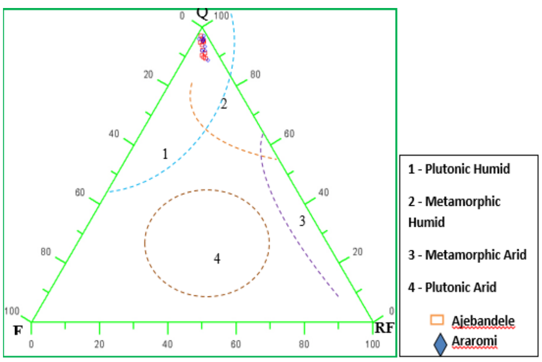


Figure 9. Palaeoclimatic settings of the sandstones from the study area (after Sutter et. al., 1981).

Whole Rock Geochemistry

Table 1. The summary of major, elemental analyses of the clastic sediments of Abeokuta Group.

		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
CS	*Min.*	79.15	9.07	3.71	0.07	0.05	0.03	0.07	0.87	0.05	0.01	0.009
	Max.	82.12	10.32	4.35	0.10	0.10	0.04	0.10	1.00	0.15	0.03	0.012
	Ave.	80.49	9.64	4.03	0.09	0.08	0.03	0.09	0.93	0.11	0.02	0.010
SST	*Min.*	72.92	0.53	0.19	0.01	0.01	0.01	0.04	0.09	0.01	0.01	0.002
	Max.	98.21	15.96	2.05	0.05	0.13	0.03	0.13	2.61	0.10	0.03	0.014
	Ave.	90.70	4.32	0.78	0.03	0.04	0.02	0.07	0.74	0.05	0.01	0.005
SH	*Min.*	35.62	15.57	1.64	0.04	0.010	0.01	0.10	0.81	0.05	0.01	0.014
	Max.	66.43	32.90	7.25	3.65	0.83	0.06	1.07	2.46	0.18	0.02	0.027
	Ave.	51.38	24.65	3.31	0.45	0.11	0.03	0.38	1.69	0.11	0.01	0.019
LST	*Min.*	10.50	10.06	2.46	0.06	30.32	0.03	0.36	0.47	0.16	0.01	0.02
	Max.	35.60	28.74	4.49	8.94	40.15	0.05	0.58	1.96	0.19	0.07	0.02
	Ave.	23.05	19.40	3.48	4.50	35.24	0.04	0.47	1.22	0.18	0.04	0.02
COAL	*Min.*	1.89	1.52	1.21	0.01	0.03	0.01	0.01	0.08	0.02	0.01	0.003
	Max.	16.37	16.38	7.92	0.03	0.03	0.02	0.16	0.66	0.06	0.01	0.014
	Ave.	9.13	8.95	4.57	0.02	0.03	0.02	0.09	0.37	0.04	0.01	0.009

	CIA	PIA	CIW	SiO_2/Al_2O_3	K_2O/Na_2O	K_2O/Al_2O_3	Fe_2O_3/K_2O	$CaO+Na_2O$
Min.	47.88	45.12	49.24	1.00	0.50	0.00	3.00	0.02
Max.	99.59	99.34	99.91	184.96	20.00	0.15	121.00	10.37
Ave.	92.87	90.41	95.13	37.58	8.51	0.03	19.46	0.57

CS-clastic sediments, SST- sandstone, SH- shale, LST- limestone
CIA- Chemical Index of Alteration PIA- Plagioclase Index of Alteration **CIW- Chemical c**

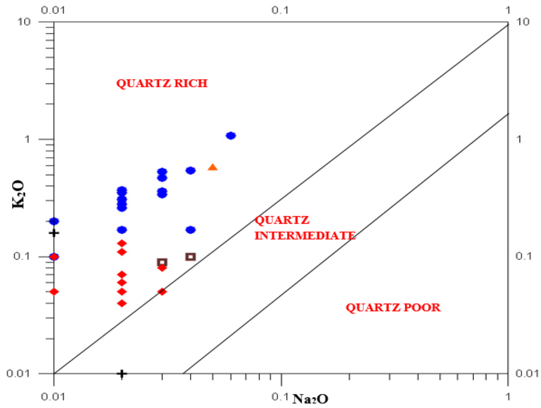


Figure 10. Analysis of sandstone based on the richness of quartz (after Crook, 1974).

Index of Weathering

Table 3. The Summary of Trace Elemental Analysis of the clastic sediments of the study area.

Trace Elements	Minimum (ppm)	Maximun (ppm)	Average (ppm)
Ba	8	301	115
Be	1	3	2
Co	0.5	56.7	10.2
Cr	20	96	60.3
Cs	0.1	4.6	1.5
Ga	0.1	41.2	18.9
Hf	0.6	70.5	13.8
Nb	1.7	51.8	23.6
Rb	0.6	46.9	11.7
Sn	1	8	4
Sr	4.7	189.7	49.9
Ta	0.1	4.2	1.7
Th	1.0	27.0	1.7
U	0.3	13.0	3.7
V	8	386	93
W	0.5	4.9	1.8
Zr	26.4	2738.1	524.9
Y	1.7	118.9	27.3
La	3.1	121.2	53.5
Ce	6.4	288.5	88.0
Pr	0.62	28.80	9.51
Nd	2.10	129.30	35.75
Sm	0.32	36.86	6.79
Eu	0.05	8.40	1.40
Gd	0.32	35.59	5.98
Tb	0.05	5.39	0.94
Dy	0.31	29.74	5.33
Ho	0.05	5.52	1.05
Er	0.19	14.98	3.01
Tm	0.03	2.00	0.44
Yb	0.23	12.90	2.92
Lu	0.04	1.87	0.44
Th/U	1.26	6.94	4.07
Zr/10	2.64	273.81	52.5
Th/Co	0.18	7.00	2.95
La/Co	0.80	20.36	8.53
Cr/Th	2.52	96.00	12.04
Eu/Eu*	-2.03	1.14	0.40
LREE	0.93	49.72	6.10
HREE	0.41	7.28	1.64
LREE/HREE	0.77	11.23	2.94
Ce/Ce*	1.36	3.42	2.39

Major Elements Geochemistry

The clastic sediments of of the study area have fluctuating values for their SiO_2. The silica in the coal ranges between 1.89% and 16.37% respectively with average of 9.13%. The shales also have low to moderate values ranging from 35.62 to 66.43% with an average of 51.77% while the sandstones are extremely rich in SiO_2(silica) ranging from 72.92 to 98.21% with an average of 90.70%, this is higher than the average of 66% by weight for Upper Continental Crust (UCC) by (Taylor and McLennan, 1985). The silica is believed to be mainly from quartz, chert, quartzite, feldspar and clay minerals (Table 2). The limestones are also low in silica as expected ranging from 35.60 to 30.01% with an average at 32.80%. The fluctuating silica content of the sediments from the well is due to the fact that they are composed of various rock types from sandstone, coal, limestone, shale, siltstone, mudstone and clayey sand. The very low value of coal SiO_2 (1.89%) is primarily due to the fact that it consists basically of volatile constituents that were combusted as is evident from the loss on ignition (95.10). The average content of Al_2O_3 for sandstone is moderate (about 4.79%) ranging from (0.54 to 19.77%). The Al_2O_3value for shale is high averaging about 25% and ranging from 15.57 to 32.90%. This may indicate high kaolinite/illite ratio within the study area (Besly and Clearl, 1997). The value of CaO is low in almost all the samples with exception of limestones where they record high values of 30.32 and 27.50 respectively. Fe_2O_3 is the most abundant major element besides Al_2O_3 and SiO_2 with an average of 2.35% (Table 2). This could be attributed to the presence of iron oxides such as haematite, ilmenite and magnetite which occur as opaque minerals. The iron oxide is also responsible for the pronounced reddish brown appearance of some of the sandstone samples. MgO is also seen to be appreciable in limestones which mean that the limestones could be dolomitic. TiO_2 with an average of 1.15 can be attributed to the presence of rutile and ilmenite because of its association with rare elements. Also, TiO_2 increases with Al_2O_3 suggesting that they are associated with phyllosillicates especially illite (Dabard, 1990). K_2O also increases from sandstones with a maximum of 0.13 to shales with a maximum of 1.07 which is an indication of the depletion of feldspars in sandstones as shown by petrographic studies. Also, the relatively high value of K_2O/Na_2O ratios especially in shales with a range of 4.25-20.00 and a mean value of 13.37 is attributed to the presence of albitic plagioclase, k- feldspar, mica and illite (Pettijohn et al., 1963, McLennan et al., 1983, Nath et al., 2000, Osae et al., 2006). Also, the very low values of K_2O/Al_2O_3 (0.01-0.15) (Table 2) suggest sedimentary recycling or increase in the degree of source area weathering (Bauluz et al., 2000). The very high average value of the ratio of SiO_2/Al_2O_3 for sandstones (87.7) is an indication of quartz enrichment (Bhatia, 1983), as compared to shales (2.20). This ratio is an indication of the weathering profile and from the high average for sandstone, it can be seen that most of the feldspar content and unstable lithic fragments has been weathered away. Also, on the Na_2O-K_2O diagram proposed by Crook (1974) (Fig. 8), the sandstone data plot in the quartz rich field. Also, a bivariant plot of SiO_2 against total Al_2O_3+K_2O+Na_2O proposed by Suttner and Dutta (1986) (Figure 9) was used in order to identify the maturity of the sandstones as a function of climate. The plot revealed semi-humid conditions for the sandstones and most other sediments with exceptions of few shale as well as limestone samples. This also gives credence to the petrographic studies. According to Herron (1988) using the standard plot of log (Fe_2O_3/K_2O) against log (SiO_2/Al_2O_3) (Fig. 12) which is a modified version of Pettijohn et al., (1972) the sediments are geochemically classified as Fe sand, Fe shale while sandstones are classified as quartz arenites. This further affirms that the sediments were ferruginised and agrees with petrographic classification of sandstones as quartz arenites, with enrichment of quartz (Table 2).

Trace Elements

Trace element geochemistry is very useful particularly for the purpose of carrying out provenance studies (McLennan et al., 1990, 1993).They can also be used to deduce the paleo-tectonic setting of sedimentary successions (Bhatia and Crook, 1986; Floyd and Leveridge, 1987; McLennan, 1989; 2001). They are also most suited for provenance and tectonic setting determinations because of their relatively low mobility during sedimentary processes and their low residence time in sea water (Holland, 1978). These elements are transported quantitatively into clastic sedimentary rocks during weathering and transportation and thus would reflect the signature of the parent materials (McLennan, 1989b).The sandstone, shales and limestones are enriched in Zr, while shales are richer in Ba, Th, V, Nb and Sr than in sandstones. Coal has very low value of Zr, and Be and enriched in Y and V which are volatile constituents of coal relative to other samples. The sandstones and shales are relatively low in Cs, Co, Sn, Be, Ta (Table 3).

Rare-Earth Elements

REE concentrations of the Ajebandele well sediments are shown by the chondrite normalised patterns according to Wakita et al., (1971), (Fig. 11). In the studied area, the sediments show relative LREE enrichment relative to HREE with a dictinctively means negative Euanormaly (0.44). Higher LREE/HREE ratios and negative Euanormalies denote felsic source rock (Taylor and McLennan 1985, Wronkiewicz and Condie 1989). This can be backed by the value of 0.44 which coincides with the range of sediments from felsic sources (0.40-0.94) (Cullers et al., 1988, Cullers, 1994; Cullers and Podkovyrov, 2000). Ce/Ce* may be used as a means of determining the environmental conditions at the time of deposition since higher values greater than 1 tentatively depict an oxidizing environment (McDaniel et al., 1994, Milodowski and Zalasiewicz, 1991) and in this case the mean value of Ce/Ce* is greater than 1 (2.39).

This goes to show that the sediments were deposited in an oxidizing environment. This could account for the high proportion of opaque minerals observed during heavy mineral analysis. The enrichment of LREE and moderately negative Eu anomaly reflect their relative abundance in the crust (Goldschmidt, 1954), while the depletion of the HREE is due to their ability to form soluble complexes in seawater (Goldberg et al., 1963).

Provenance and Tectonic Setting

Several classifications have been proposed to discriminate various tectonic settings (Maynard et al., 1982; Bhatia, 1983; Bhatia and Crook, 1986; Roser and Korsch, 1986). To infer provenance, un-standardized discriminant function scores of the samples for major elements were plotted on a diagram (Fig. 13) which was demarcated into fields which are mafic igneous provenance, quartzose sedimentary provenance, felsic igneous and intermediate igneous provenance fields as proposed by Roser and Korsch (1988). Sediments of Abeokuta Group fell within the recycled mature polycyclic quartzose detritus otherwise known as quartzose sedimentary field and intermediate igneous provenance with some sediments also falling in the felsic provenance field. Recycled sources represent quartzose sediments of mature continental provenance and this can be ascertained from by QFL ternary plots as proposed by Dickinson and Suczek (1979) (Fig. 8) and the derivation of the sediments could be from a highly weathered granite-gneiss terrain and/or from a pre-existing sedimentary terrain Roser and Korsch (1986). The recycled nature of the sediments is also reflected from the modal composition. The sandstones have a dominantly quartzose composition with predominance of quartz, little feldspars and low grade metamorphic lithics. Also recycled sediments and sedimentary rocks allow expected enrichment of Zr, reflecting zircon addition as seen from the heavy mineral studies (McLennan et al., 1990; Zimmerman and Bahlburg, 2003). This is true as majority of the sediments fell within the recycled mature polycyclic quartzose detritus. Also, some of the sediments fell in the intermediate igneous provenance. This only goes to show that the sediments of the study area were sourced from mixed environments of acid igneous, metamorphic and sedimentary rocks.

The High Field Strength Elements (HFSE) such as Zr, Nb, Hf, Y, Th, are preferentially partitioned into melts during crystallization (Feng and Kerrich, 1990) and as a result, these elements are enriched in felsic rather than mafic sources. These elements are thought to reflect provenance compositions as a consequence of their generally immobile behavior (Table 5) (Taylor and Mclennan, 1985). The REE and Sc also give indications of source compositions because of their low mobility during sedimentation and their low residence time in seawater (Bhatia and Crook, 1986). Mafic and felsic source rocks differ significantly in the ratios such as Eu/Eu*, $(La/Lu)_N$, La/Sc, Th/Sc, La/Co, Th/Co ad Cr/Th and hence provide useful information about the provenance of sedimentary rocks (Cullers et al., 1988; Cullers, 1994; Cullers and Padkovyrov, 2000). In this study, Eu/Eu*, $(La/Lu)_N$, La/Sc, Th/Sc, La/Co, Th/Co and Cr/Th values are similar to values of sediments derived from felsic source rocks rather than to those of mafic source rocks.

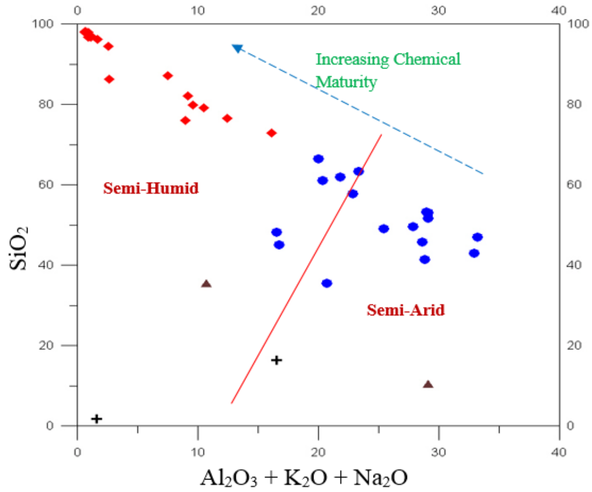


Figure 10. Chemical composition of Sandstones (after Pettijohn, 1975).

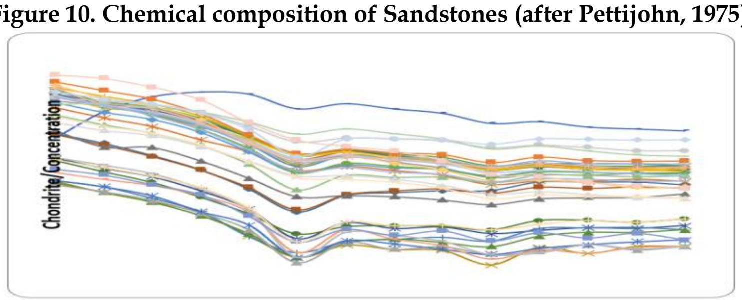


Figure 11. Chondrite Normalized Spider Diagrams for Rare-Earth Elements.

Also, higher LREE/HREE ratios and negative Euanornaly of the Ajebandele well sediments bears the characteristics of felsic source rocks (after Taylor and Mclennan 1985; Wronkiewicz and Condie, 1989). The ferromagnesian trace elements Cr, Ni, Co and V show generally similar behavior in magmatic processes but they may be fractionated during weathering (Feng and Kerrich, 1990). In the studied samples, Cr and Ni are enriched with respect to the average composition of the upper continental crust (UCC). This enrichment of Cr and Ni may suggest some basic input from the source terrain. The elevated values of Cr (>150ppm) and Ni (>100ppm) and the ratio of Cr/Ni between 1.3-1.5, are diagnostic of ultramafic rocks in the source region (Garver et al., 1996). In comparism, Cr concentrations range from 20 to 83 with an average of 58.14, while Ni ranges from 20 to 94 with an average of 30.6. Cr/Ni ratios vary from 0.82-4.80 but they are mostly less than 2.0. This comparism implies that the existence of widespread mafic to ultramafic rocks in the source region was unlikely. Also, the Co enrichment which has a value of 9.3 which is lower than the Average Upper Continental Crust (AUC) (10.00) confirms a much reduced mafic input from the source area (Table 3) (Taylor and McLennan, 1985). Therefore it can be concluded that sediments of the study area are derived from mixed environments but with predominance from felsis sources.

Dickinson and Suczek (1979) proposed a QFL (Fig. 8) ternary to discriminate the sediments, and they were seen to plot in the continental arc as well as recycled orogen provenance. Bhatia and Crook (1986) used La, Th and Sc concentrations as well as Th, Sc and Zr/10 and Th, Co and Zr/10 concentrations to discriminate sediments derived from oceanic island arc, continental island arcs, active and passive continental margins. Using La-Th-Sc ternary plots, the sediments from Ajebandele well plotted in the continental island arc (Fig. 14).

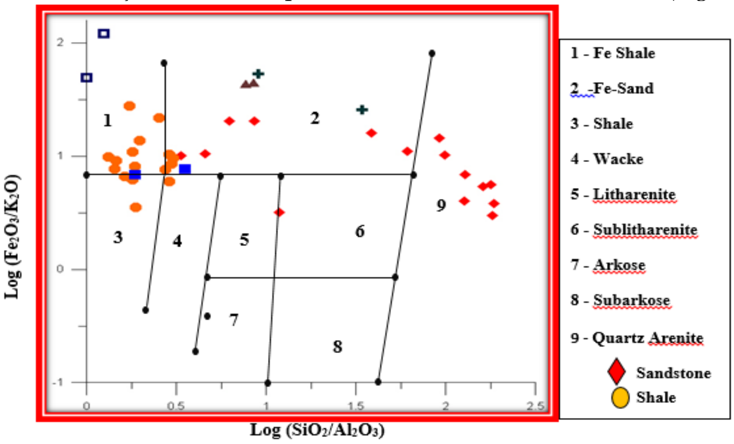


Figure 12. Chemical classification of Siliclastic sediments of Abeokuta Group sediemnts (After Herron, 1988).

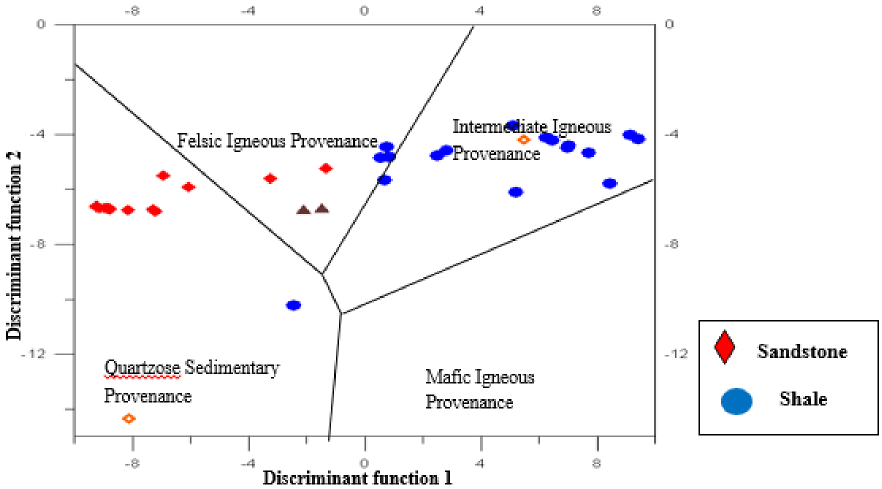


Figure 13. Discriminant Function diagram for the provenance signature of the studied area using raw oxide (based on Roser and Korsch, 1988).

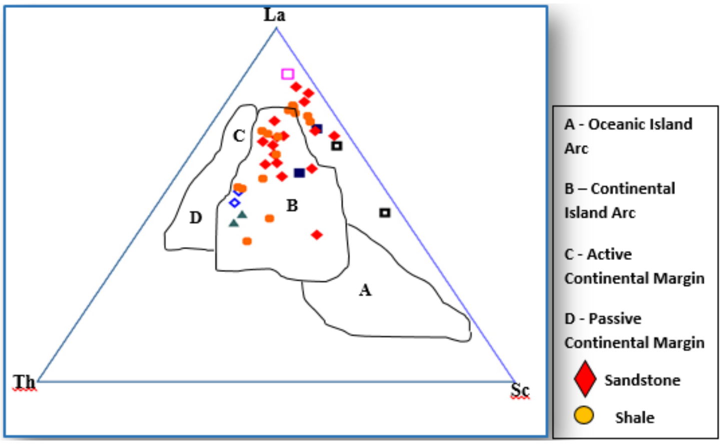


Figure 14. La- Th-Sc Ternary Plots for Abeokuta Group Sediments (After Bhatia and Crook, 1986).

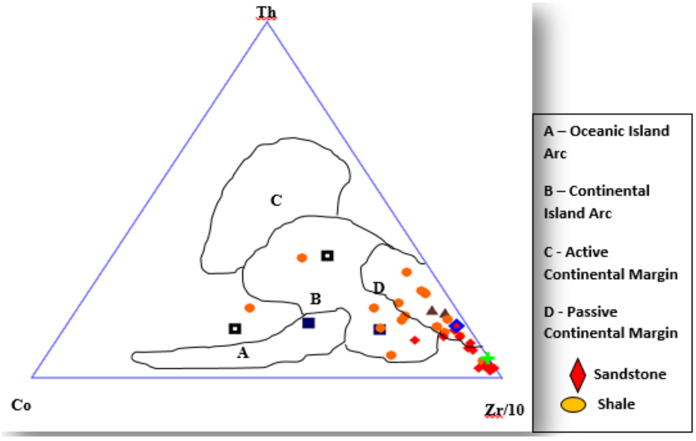


Figure 15. Th-Co-Zr/10 Plots for the Abeokuta Group Sediments (After Bhatia and Crook, 1986).

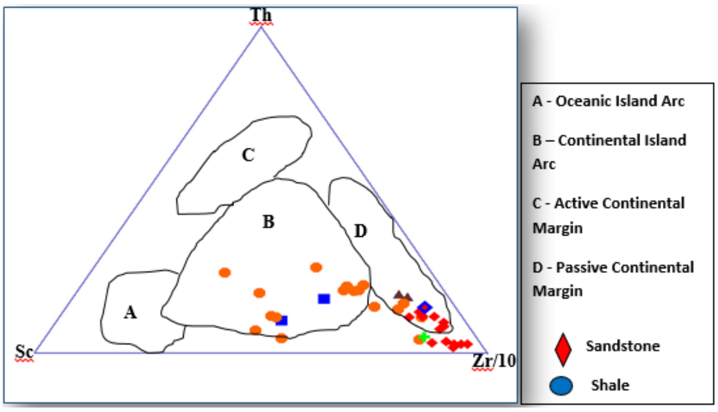


Figure 16. Th-Sc-Zr/10 Plots for Abeokuta Group Sediments (After Bhatia and Crook, 1986).

Table 3. Range of Elemental Ratios from the study area compared to other siliciclastic sediments from other sources.

Elemental Ratio	Abeokuta Group Sediments	Range in sediments from felsic sources[1]	Range in sediments from mafic sources[1]	Upper continental crust[2]
Eu/Eu*	-2.03-0.89	0.40-0.94	0.71-0.95	0.63
$(La/Lu)_N$	0.94-19.28	3.00-27.00	1.10-7.00	9.73
La/Sc	0.98-9.50	2.50-16.30	0.43-0.86	2.21
Th/Sc	0.48-2.08	0.84-20.50	0.05-.002	0.79
La/Co	0.80-20.36	1.80-13.80	0.14-0.38	1.76
Th/Co	0.28-7.00	0.04-3.25	0.04-1.40	0.63
Cr/Th	3.28-96.00	4.00-15.00	25-500	7.76
Co (ave)[C]	9.3	-	-	10.00

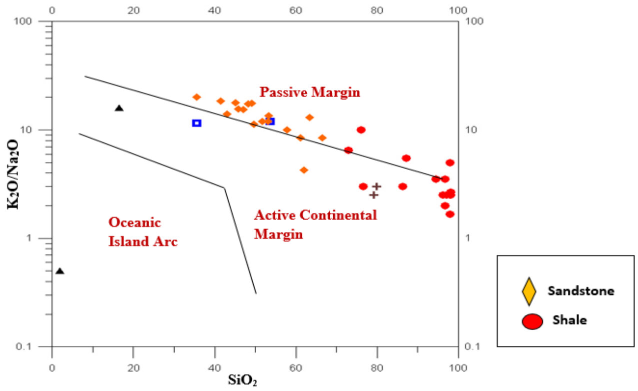


Figure 17. Tectonic Discriminant diagram for Abeokuta Group Sediments (After Roser and Korsch, 1986).

Th-Co-Zr/10 and Th-Sc-Zr/10 ternary plots revealed that the sediments showed affinity for continental island arc and passive margin settings (Figs. 15 and 16). In addition, Roser and Korsch (1986) established a discriminating diagram using log (k_2O/Na_2O) Vs SiO_2 (Fig.17) to determine tectonic settings of the studied samples. From the diagram, the sediments showed affinity for the active continental margin to passive margin settings. From these plots, it can be seen that the source of these sediments are uplifted terrains of folded and faulted strata from which recycled detritus of sedimentary and metasedimentary origin were input into the basin (Dickinson and Suczek, 1979, Boggs 2006).

Source Area Weathering

The weathering history of ancient sedimentary rocks can be evaluated in part by examining relationships among the alkali and alkaline earth elements (Nesbitt and Young, 1982). This is because alteration of igneous rocks during weathering results in depletion of alkali and alkaline earth elements and preferential enrichment of Al_2O_3 in sediments. The most widely used indices for quantitative estimation of the degree of chemical weathering undergone by clastic sediments or rocks from the source area include; the Chemical Index of Alteration (CIA) proposed by Nesbitt and Young (1982), and Plagioclase index of Alteration (PIA) by (Fedo et al., 1995). High CIA and PIA values (75-100) indicate intensive weathering in the source area whereas low values (≤60) indicate low weathering in the source area (Osae et al., 2006). Other indices also used are that of Chemical Index of Weathering (CIW) (Harnois, 1988). Summary of CIA, PIA and PIW values are shown in (Table 2).

The CIA=100[Al_2O_3/ (Al_2O_3+CaO+Na_2O+K_2O)]

The PIA=100[(Al_2O_3-K_2O) / (Al_2O_3+CaO+Na_2O-K_2O]

The CIW=100[Al_2O_3/ (Al_2O_3+CaO+Na_2O)]

The CIA, PIA and CIW values range from (72.60-99.59%, 65.75-99.34%, and 77.94-99.91%) with averages of (99.59%, 99.34% and 99.91%) respectively. The limestone samples averages 47.41%. This low value is due to the fact that the limestones were likely derived from the least weathered zones of the soil profile. The CIA values were also plotted in Al_2O_3 - (CaO + Na_2O) - K_2O (A - CN - K) diagram (Fig. 18). In the A-CN-K diagram, the sediments plotted mostly within the kaolinite-chlorite region, with some within the smectite-illite range as well.

The fact that the samples did not plot very close to the plagioclase-k-feldspar join line is an indication of high weathering at the source. The occurrence of abundant quartz, negligible feldspar and lithic fragments of the sandstones as well as kaolonite and chlorite rich clay assemblages (Rahman and Faupl, 2003a, b) implies that the minerals are predominantly detrital and reflect the character of their source material after (Weaver, 1958). The thick pile of inter-bedded sandstones and shales may have been resulted from rapid erosion of fast rising orogens. Also, the relationship between Th/U ratio and Th concentration can also be applied as an estimate of the degree of weathering in sedimentary rocks. Both Th and U are relatively immobile during weathering, although, U may change its redox state from U^{2+} to U^{6+}, (the latter being more soluble) during re-working under oxidising conditions as this is the case and it is thus more readily removed from the system thereby increasing the Th/U ratio above upper crust igneous values. The Th/U ratio from upper continental rocks range from 3.5 to 4.0 (McLennan et al., 1993). In sedimentary rocks, Th/U values higher than 4.0 may indicate intense weathering in the source areas or sedimentary recycling. Th/U ratios of the sediments range from 1.26-6.94 and this is an indication of intense weathering in the source area or sediment recycling. Sediments from active margin tectonic settings have Th/U significantly below 3.5 accompanied by low Th and U contents (Fig. 19) and this is interpreted as dominantly reflecting a low ratio in the source rock (McLennan 1989b, McLennan and Taylor, 1990). This can be seen for the sediments of the study area which have a variable proportion of low Th/U ratios. Low Th/U ratios which are rather common in mantle derived volcanic rocks and reflect the geochemically depleted nature of such reservoirs (Newman et al., 1984). Also, it is worthy of note to add that high Th/U ratios are seen in recycled sedimentary source rocks (according to McLennan et al., 1993) and this is also reflected in the sediments because an appreciable percentage of the sediments have high Th/U ratios as well. From this, it can also be ascertained that the Ajebandele sediments are from both active continental margins as well as passive margins which translates into mixed environments for the sediments. Sedimentary sorting and recycling can be monitored by a plot of Th/Sc against Zr/Sc (McLennan et al., 1993). First order sediments show a simple positive correlation between these ratios whereas recycled sediments show a substantial increase in Zr/Sc with far less increase in Th/Sc. The trend of increasing Zr/Sc and almost constant Th/Sc can be exhibited by first cycle sediments if they are derived from largely plutonic sources as described by Roser and Korsch (1988). On the Th/ScVsZr/Sc diagram the sandstones follow a somewhat general trend consistent with their direct derivation from igneous rocks (Fig. 21). This further helps to confirm igneous sources for the sediments.

Depositional Environments

The depositional environments for sediments of the Abeokuta Group were classified based on the ternary plots of Englung and Jorgensen (1973). This involves the chemical classification on the basis of Al_2O_3-K_2O+ Na_2O+CaO-Fe_2O_3+MgO contents (AKF). As can be observed from the plots, there is a gradual transition of the sediments from continental to transitional environments which depicts a somewhat shallow-marine environment, (Fig. 20). However, sediments are dominantly ferruginous argillites. This goes to show that some of the sediments were transported from the continental environment before being deposited in the shallow-marine environment elucidating the fact that the sediments underwent moderate to high transportation levels under oxidizing conditions. Also, Folk (1974), linked textural maturity to environment of deposition in that texturally immature sediments are found in low to medium energy neritic environment, whereas the sub-mature to mature textured sediments are found in high energy neritic environment. The studied sediments were seen to be mature and this agrees with the fact that the sediments were deposited in shallow-marine environments. This also goes to explain the high levels of quartz grains especially for the sandstones with reduced feldspar and rock fragment as well as petrographic and geochemical classification which classified them as quartz arenites (Folk, 1968). This also corresponds with the lithologic description (Figs 3 and 4).

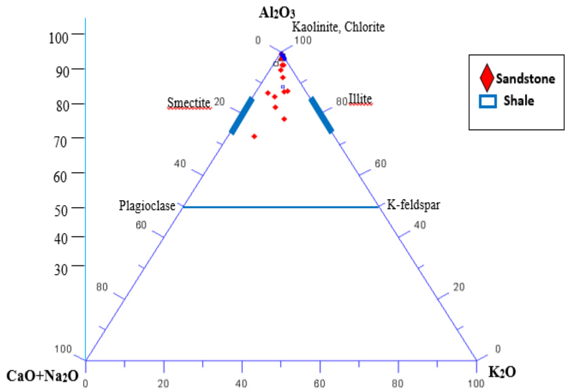


Figure 18. CIA ternary diagram Al2O3-CaO+Na2O-K2O (after Nesbitt and Young, 1982).

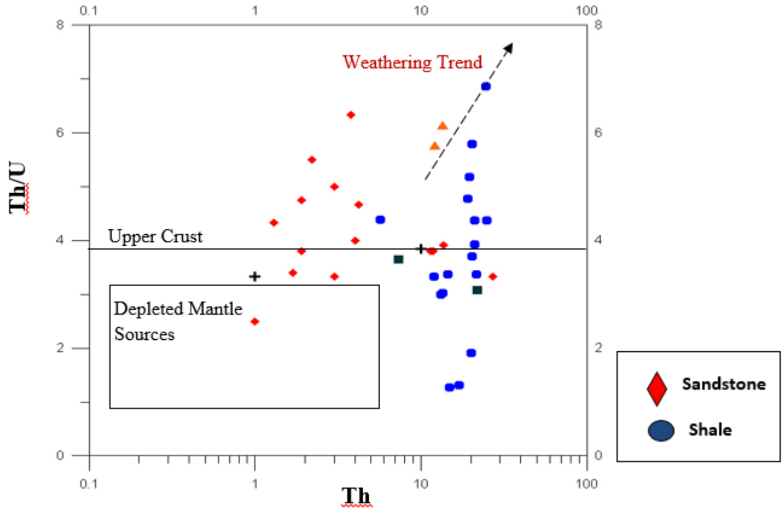


Figure 19. Plot of Th/U versus Th showing the weathering trend (after Mclennan et al., 1993).

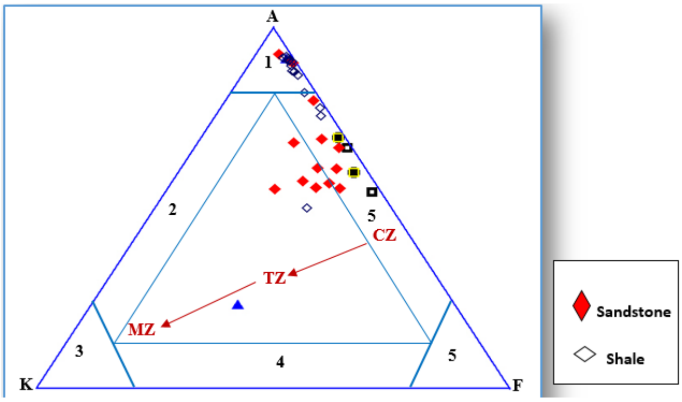


Figure 20. Al2O3 - (K_2O+CaO+MgO) - (Fe_2O_3+MgO) [AKF] Ternary plots for sediments of the study area (Englund and Jorgensen, 1973).

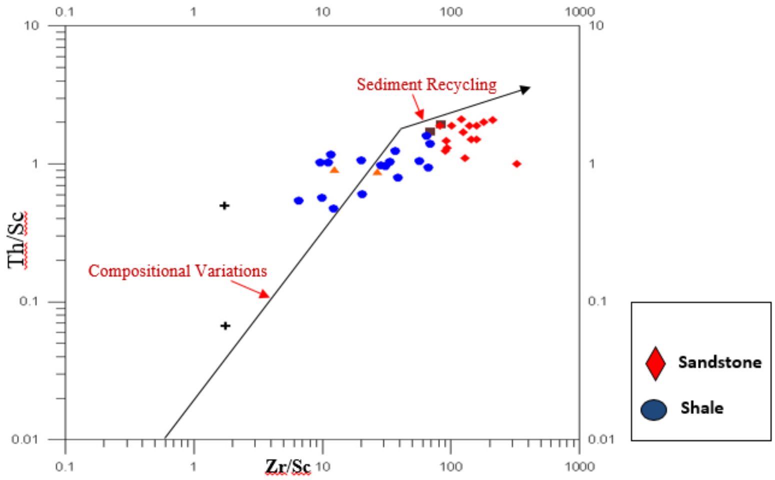


Figure 21. Th/Sc versus Zr/Sc for the Sediments of the study area (after Mclennan et al., 1993).

CONCLUSION

The sediments of Abeokuta Group have a dominantly quartzose composition with very little feldspar and lithic fragments indicating that the sands were derived from a quartzose recycled orogen province with long transportation history under humid conditions as well as a slow sedimentation rate. Heavy mineral assemblages suggest mixed environments for the sediments and limestone petrography indicates shallow marine environments.

SiO_2 content for the sandstones of the study area is high with a mean value of 90.70%, higher than the average of 66% by weight for Upper Continental Crust (UCC) by Taylor and McLennan (1985). Consequently, they are depleted in Al_2O_3, CaO, MgO and other major oxides. Shales however, have low to moderate values of SiO_2 and higher values of Al_2O_3 compared to sandstones. The limestones have very low values of SiO_2 and higher values of Al_2O_3, CaO and MgO which suggests it could be a combination of calcite and dolomite. Discriminant function plots for provenance reveals that the sediments are derived from quartzose sedimentary, felsic igneous and intermediate igneous provenances backing up heavy mineral studies that they are sourced from mixed environments. Tectonic setting diagrams reveal active continental margin to passive margin settings. CIA, PIA and CIW values which are averagely 93.83, 91.32 and 96.15 point to intensive weathering for the sediments except for limestone that has low values averaging 47.41 which suggests that it could have been derived from the least weathered zones of the soil profile. The trend of increased Zr/Sc (80.43%) against the very low values of Th/Sc is a clear indication of sediment recycling which also supports the weathering trend of the sediments and generally supports the petrographic studies.

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