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Heavy Minerals and Geochemical Characteristics of Sandstones as Indices of Provenance and Source Area Tectonics of the Ogwashi-Asaba Formation, Niger Delta Basin

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Abstract

Heavy mineral petrographic and geochemical compositions (major and trace/rare earth elements) of sandstones obtained from the Oligocene-Miocene Ogwashi-Asaba Formation, Niger Delta were studied to determine their provenance, source area weathering conditions and tectonic setting. The heavy mineral suite (opaque minerals, zircon, tourmaline, and rutile) revealed that the sandstones are mineralogically mature and implied rapid disintegration and chemical decomposition of sediments mostly of recycled orogen. The sandstones were geochemically classified as Fe-sand and partly quartz arenitic. Chemical Index of Alteration and Chemical Index of Weathering values of 89.92% and 91.87% respectively suggest that the source region was predominantly felsic and was subjected to intense chemical weathering probably under tropical palaeoclimatic conditions with abundant rainfall that enhanced sediment recycling. Major element concentration discriminant plots also indicated that the sediments were derived from mixed sources (granitic, gneissic or recycled orogen) under passive margin setting. Chondrite normalized plot of the rare earth element pattern is marked by light rare earth element enrichment and negative Eu anomalies, interpreted to mean that provenance was mainly continental crustal rocks. Trace elemental ratios that are provenance diagnostic (La/Sc, Th/Sc, Cr/Th, La/Co, Th/Co, Th/Cr, Eu/Eu*, and Eu*) all point to sediments derived from felsic source and upper continental crust. The mixed provenance of the sandstones can be traced to the southwestern and southeastern Basement Complex (consisting of granites, gneisses, etc.) and sediments derived from the adjacent sedimentary basins (Anambra and Benue Trough).

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Keywords

Provenance, Source Area Tectonics, Heavy Minerals, Geochemical Characteristics, Sandstones, Ogwashi-Asaba Formation, Niger Delta Basin

1. Introduction

Provenance and other related studies associated with tectonic settings and palaeo-climatic conditions that determined weathering processes in the source areas of the Akata Formation, the Agbada Formation and Benin Formation that constitute the sedimentary fill of the Niger Delta Basin are lacking as emphasis has always been on the hydrocarbon potential of these formations. The lignite-bearing Ogwashi-Asaba Formation which is the surface equivalent of the Agbada Formation is no exception as only limited studies have specifically examined its hydrogeology [1]; aspects of the lignite geochemistry [2]; combined petrological, geochemical and sedimentological study [3]; and a textural and geochemical study for the determination of its depositional setting [4].

The primary objective of this investigation is to utilize heavy mineral and geochemical data to determine the provenance, tectonic setting of source area and palaeo-climatic conditions associated with the deposition of the Ogwashi-Asaba Formation. Similar research on provenance of siliciclastic sedimentary rocks has usually been focused on sandstones and has in the main been based on petrographic analysis of quartz, feldspars, micas and heavy minerals. However, ancillary techniques such as cathodoluminescence microscopy [5] and the geochemical studies of major, trace and rare earth elements and isotopes in siliciclastics have also been used. The use of heavy minerals (the components of siliciclastics whose specific gravity is greater than that of bromoform (2.8)) is a universally accepted method for determining the provenance of siliciclastics [6] [7] because they *resist* relatively the physiochemical alteration associated with source area weathering, erosion and diagenesis [8] and thus retain and *bear* the source rock characteristics from which they were derived.

Indeed, geochemical data from sandstones sequences deposited in various environments provide invaluable clues on ancient source area weathering conditions, variations in provenance compositions and tectonic settings [9]-[13]. The characteristic compositions of source rocks are also typically well recorded in the sedimentary fills which furnish valuable information about the type of source rocks and their tectonic setting [14]-[22].

2. Geology and Stratigraphic Setting of the Niger Delta Basin

Firs Adediran *et al.* [23] described the coastal sedimentary basins (Dahomey, Anambra, Niger Delta and Calabar Flank) of Nigeria as open-type, developed along the passive continental margin of the Gulf of Guinea and filled with continental deposits. The drifting apart of the South American continent from the African continent during the late Jurassic or early Cretaceous has been closely related to the spatial distribution of these basins [24]. The Niger Delta basin occupies the southern end of the Anambra basin that is adjacent to the Benue Trough, formed as a result of a failed arm of a triple junction such that rifting ceased in the late Cretaceous [25]. The Niger Delta thus evolved in the late Cretaceous through rift induced tectonics that ended with the opening of the Gulf of Guinea [26].

The coastal sedimentary basins of Nigeria have been through three depositional cycles [27] [28]: first, a mid-Cretaceous marine incursion that ended by mild folding during Santonian; a second cycle that led to the development of the proto-Niger Delta during the Campanian and concluded in a major transgression in the Paleocene. The third sedimentary cycle lasted from Eocene to Recent, leading to the unremitting development of the main Niger Delta. The major thrust of this paper deals with the third cycle, especially from Oligocene to Miocene.

The spatial and temporal distribution of the Niger Delta facies can be grouped into the outcropping and subsurface Tertiary sections **Table 1** [27] [29]-[31]. The Akata Formation, Agbada Formation and the youngest Benin Formation make up the subsurface section while the surface and outcropping facies equivalents are respectively, the Imo Formation, Ameki Formation, Ogwashi-Asaba Formation and Benin Formation [32]. The Imo Formation (Paleocene to early Eocene) is known to exhibit blue-grey shales with sand lenses, marls and fossiliferous limestones. The Ameki Formation (Eocene to early Oligocene), sometimes referred to as the Ameki Group [33] is characterized by calcareous clays and silts with thin shelly limestone, rich in foraminifera, also mainly sands with minor silt and clay intercalations. Reyment [32] suggested the name Ogwashi-Asaba Formation (also

Table 1. Comparisonof the facies of present-day with the Teriary units of the Niger Delta (after Maron [29]).

Present Niger Delta	Outcrops of tertiary strain	Subsurface formation
NEDECO Report, 1954	Reyment, 1965	Short and Stäuble, 1967
Continental (fluviatile) deposits, mainly sands	Benin Formation	Benin Formation Afam Clay Member
Mixed continental brackish water and marine deposits, sands and clays	Ogwashi-Asaba Formation Ameki Formation	Agbada Formation
Marine deposits, mainly clays	Imo shales	Akata Formation

the age, Oligocene-Miocene) to replace the "lignite series" of Parkinson [34] and is made up of lignite seams, clay, shales/carbonaceous mudstones and cross-bedded sandstones. The Benin Formation (Oligocene to Recent) is also marked by cross-bedded, coarse-pebbly continental sands, with clay lenses.

3. Material and Methods

Eighteen sandstone samples were obtained from active quarry sites located in the Asaba Capital Territory and Ibusa, **Figure 1**. These representative samples were carefully obtained from different levels of each quarry from the base to the top, **Figure 2**. A subset of twelve (12) samples out of the sampled masses was reduced to 10 g of sediments each by coning and quartering and prepared for heavy mineral separation. The samples were thereafter washed separately to remove clay-sized fractions and boiled with HCl acid (1:1) for 10 minutes to remove iron coatings and cementing material. They were then washed and dried a second time and thus made ready for heavy mineral separation (gravity method). Separation of the heavy from light minerals was done using bromoform ($CHBr_3$) as the separating liquid. The extracts of bromoform containing the heavy minerals were rinsed with acetone and thereafter mounted on glass slides. A quantitative estimation [point-counting method of the opaque and non-opaque fractions (ultra-stable and meta-stable groups)] of the heavy minerals present in the sandstones was done by studying them under the binocular petrological microscope at the Petrology Laboratory, Department of Geology, University of Ibadan, Nigeria.

A second subset of six (6) selected samples was air dried, homogenized by coning and quartering and reduced to 10 g. Aliquots of 10 g of each dried sample were powdered in an agate mortar. Further preparation and analytical procedures of samples are as outlined in Jarvis and Jarvis [35] and Pearce *et al.* [36].

Major element oxides and trace/rare earth elements (Sc, Be, V, Sr, Y, Zr, and Ba) concentrations were determined by Fusion Inductively Coupled Plasma (FUS-ICP) with a detection limit of 0.001% - 0.1%. Other trace and rare earth elements were determined by Fusion Mass Spectrometry (FUS-MS) with a detection limit of 0.04 - 30 ppm. These two analytical packages gave results that comprised 10 major elements (oxides and loss on ignition), in addition to 18 trace and 14 rare earth elements respectively. These analyses were done at the Activation Laboratories Limited, Ontario, Canada.

4. Results

4.1. Heavy Mineral Petrography

The heavy mineral assemblage consists of opaque minerals (e.g. haematite), zircon, rutile, tourmaline, garnet, sillimanite and apatite, in decreasing order of abundance displayed in **Table 2** and **Figure 3**. Thus the opaques have the highest proportion of 42% of the total heavies while the non-opaques, zircon and rutile account for 26% in equal proportion, followed by tourmaline which is 12%. Garnet, sillimanite and apatite consist of 8%, 7%, and 5% respectively.

Zircon showed prismatic, sub-hedral grains that have prominent crystal faces. It's colourless, exhibiting high relief and birefringence. Modal composition varies from 9.09% to 17.78% of the total heavies. Elongated, prismatic, pleochroic, and sub-rounded grains were indicated by tourmaline with colour variations from brown, greenish brown to dark green. Tourmaline modal composition varies from 8.89% to 13.95% of the total heavies. Rutile is reddish brown, weakly pleochroic, and with very high relief. Rutile percentage proportion varies from 11.11% to 18.60% of the total heavies. Garnet was identified as colourless to light purple, sub-angular and high

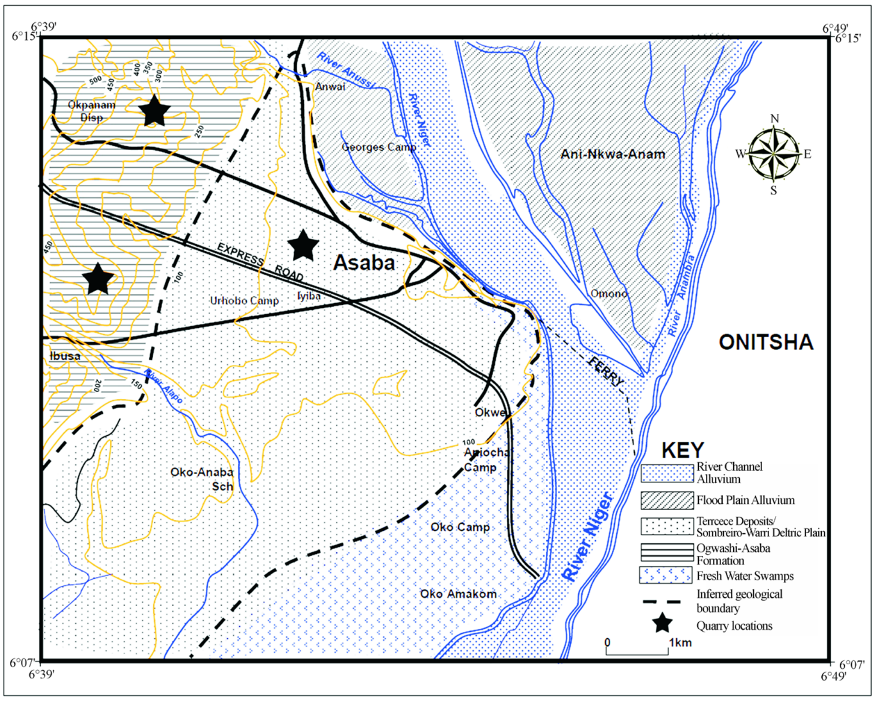

Figure 1. Sample locations on a geological map of Asaba and surrounding areas (modified after Akpoborie *et al.* [1]).

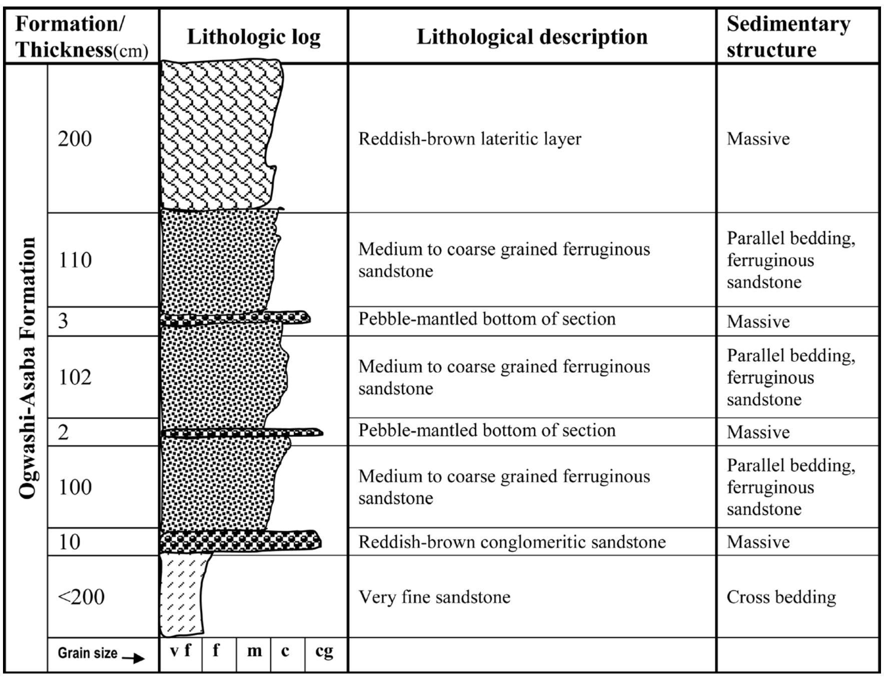

Figure 2. A representative lithological section of the Ogwashi-Asaba Formation observed at Ibuse quarry site.

relief. Apatite is usually colourless with moderate relief. The modal composition of apatite ranges from 3.03% to 7.14% while the modal percentage composition of garnet varies from 4.76% to 11.62% of total heavies.

Estimates of the Z.T.R. mineralogical maturity indices [36] derived as the ratio of the combined modal composition of zircon (Z), tourmaline (T), and rutile (R) to that of the transparent, non-micaceous and detrital heavy

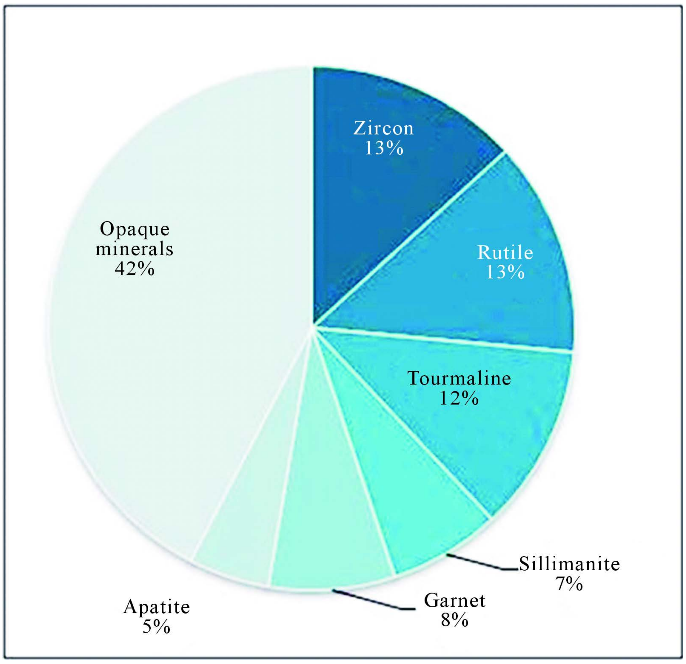

Figure 3. Relative proportions of heavy minerals in the sanstones of the study area.

Table 2. Relative proportions of heavy ninerals (in %) in the sanstones of the Ogwashi-Asaba Formation.

Sample code	Zircon	Rutile	Tourmaline	Sillimanite	Garnet	Apatite	Opaque minerals
IBS L4A	13.95	11.62	13.95	6.97	6.97	4.65	41.86
IBS_L2D	12.50	12.50	10.42	8.33	6.25	4.17	45.83
IBS_L5A	9.30	13.95	11.63	6.97	11.62	6.97	39.53
IBS_L4B	11.11	11.11	13.89	5.56	8.33	5.56	44.44
IBS_L1B	9.09	12.12	9.09	6.06	6.06	3.03	54.54
IBS_L2A	14.63	12.19	12.19	4.87	9.76	4.88	41.46
IBS_L3B	9.30	18.60	11.63	6.98	6.97	4.65	41.86
IBS_L2C	16.27	13.95	11.62	6.97	9.30	4.65	37.21
IBS_L4D	14.28	14.28	11.90	7.14	7.14	4.77	40.47
IBS_L3E	17.78	11.11	8.89	6.67	8.89	4.44	42.22
IBS_L3A	14.28	14.28	9.52	7.14	4.76	7.14	42.85
IBS_L1A	15.90	13.63	13.63	9.09	6.82	4.54	36.36
Average	13.20	13.28	11.53	6.89	7.74	4.95	42.39

minerals and expressed as percent for each sample (**Table 3**), range from 58% to 68% with an average of 66.99%.

4.2. Major Element Geochemistry

The compositions (wt.% of oxides) of major elements of the representative sandstone samples are presented in **Table 4**. The clearly quartz-rich sandstones have SiO_2 content that range between 71.42 wt% and 90.84 wt%. They are also depleted of TiO_2, MnO, P_2O_5, the alkalis (Na_2O and K_2O) and alkali earth elements (MgO and CaO). This parallel depletion can be attributed to the weathering conditions in the source area. In contrast the Fe_2O_3 and Al_2O_3 show high and slight enrichment respectively. Herron's [38] log-log plot of (SiO_2/Al_2O_3) versus

Table 3. Percentages of Zircon, Tourmaline, Rutile and Z.T.R. index of sandstones of the Ogwashi-Asaba Formation.

Sample code	Zircon	Tourmaline	Rutile	ZTR index
IBS L4A	24.0	24.0	20.0	68
IBS_ L2D	23.0	19.2	23.1	65
IBS_L5A	15.4	19.2	23.1	58
IBS_ L4B	20	25.0	20.0	65
IBS _L1B	20.0	20.0	26.7	67
IBS_L2A	25.0	20.8	20.8	67
IBS_L3B	16.0	20.0	32.0	68
IBS_L2C	25.9	18.5	22.2	67
IBS_L4D	24.0	20.0	24.0	68
IBS_L3E	30.8	15.4	19.2	65
IBS_L3A	25.0	16.7	25.0	67
IBS_L1A	25.0	21.4	21.4	68
			Average	66.99

Table 4. Major element compositions (wt.%) for sandstones from the Ogwashi-Asaba Formation [4].

Rock type	Ferruginized sandstones			Non-ferruginized sandstones		
Sample #	**IBS_L2E**	**IBS_L3E**	**IBS_L2B**	**IBS_L1C**	**IBS_L2A**	**IBS_L3B**
SiO_2	71.42	76.57	78.51	87.48	90.84	92.76
TiO_2	0.294	0.033	0.041	0.119	0.177	0.098
Al_2O_3	1.59	1.13	1.46	1.13	1.85	1.38
Fe_2O_3*	21.42	19.12	16.79	9.48	4.84	3.63
MnO	0.025	0.012	0.014	0.015	0.01	0.011
MgO	0.03	0.02	0.02	0.01	0.01	0.02
CaO	0.02	0.02	0.09	0.02	0.02	0.44
Na_2O	0.05	0.04	0.05	0.03	0.04	0.05
K_2O	0.03	0.04	0.03	0.03	0.03	0.03
P_2O_5	0.38	0.28	0.25	0.18	0.1	0.03
LOI	3.52	3.02	2.84	1.62	1.32	1.69
Total	**98.78**	**100.3**	**100.1**	**100.1**	**99.24**	**100.1**
MgO + Fe_2O_3*	21.45	19.14	16.81	9.49	4.85	3.65
Fe_2O_3*/K_2O	714	478	559.7	316	161.3	121
CaO* + Na_2O	0.0012	0.0010	0.0016	0.0009	0.0010	0.0016
Al_2O_3/TiO_2	5.408	34.242	35.609	9.496	10.452	14.082
K_2O/Na_2O	0.6	1.0	0.6	1.0	0.75	0.6
SiO_2/Al_2O_3	44.92	67.76	53.77	77.42	49.10	67.22
Moles						
SiO_2	1.1886	1.2743	1.3065	1.4558	1.5117	1.5437
Al_2O_3	0.0156	0.0111	0.0143	0.0111	0.0181	0.0135
CaO*	0.0004	0.0004	0.0008	0.0004	0.0004	0.0008
Na_2O	0.0008	0.0006	0.0008	0.0005	0.0006	0.0008
K_2O	0.0003	0.0004	0.0003	0.0003	0.0003	0.0003
CIA	91.228	88.800	88.272	90.244	93.299	87.663
CIW	92.857	91.735	89.937	92.500	94.764	89.404

Note: Fe_2O_3* refers to total Fe, CaO* represents Ca in silicate minerals only (*i.e.*, excluding calcite, dolomite and apatite) [46]. An approximate correction for carbonate content was done by assuming reasonable Ca/Na ratios in silicate materials [15].

(Fe_2O_3/K_2O) for the samples is shown in **Figure 4**, in which sandstones of the study area fall mostly within the Fe sand field.

4.3. Trace Element Geochemistry

Concentrations of trace elements and elemental ratios of the sandstones are shown in **Table 5**. The sandstones are enriched in Zr, with minor enrichment in Y, Nb, Th, Hf, and U. Ta is depleted. These elements are essential components of heavy minerals such as zircon. They are less common in mafic rocks, but enriched in felsic rocks. Ratios of trace elements such as La/Sc, Th/Sc, Co/Th, Cr/Th, La/Co, Th/Co, Th/Cr, Eu/Eu*, and Eu* in siliciclastic rocks such as sandstones have been used to infer the average provenance composition [14] [39] [40]-[45].

4.4. Rare Earth Element Geochemistry

The rare-earth element concentrations of the sandstones are presented in **Table 6**. **Figure 5** indicates their chondrite normalized rare earth element (REE) pattern, marked by light rare earth element (LREE) enrichment and

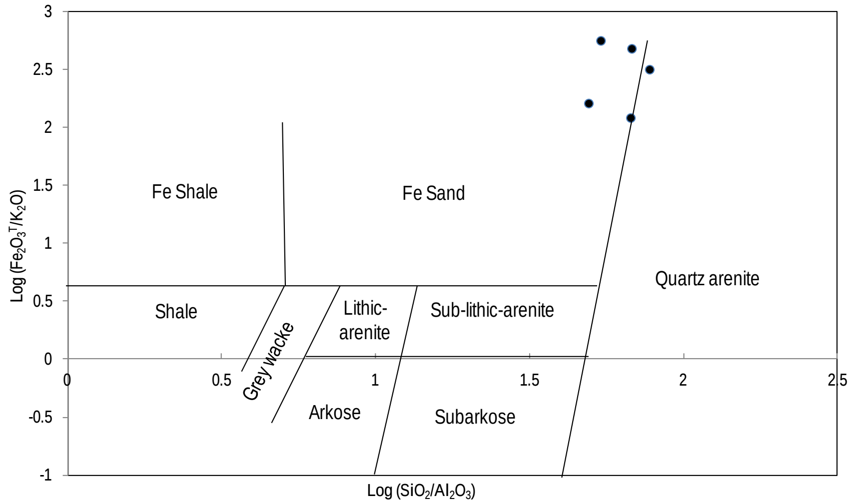

Figure 4. Log (Fe_2O_3/K_2O) versus log (SiO_2/Al_2O_3) (after Herron, [38]) for sandstones of the Ogwashi-Asaba Formation.

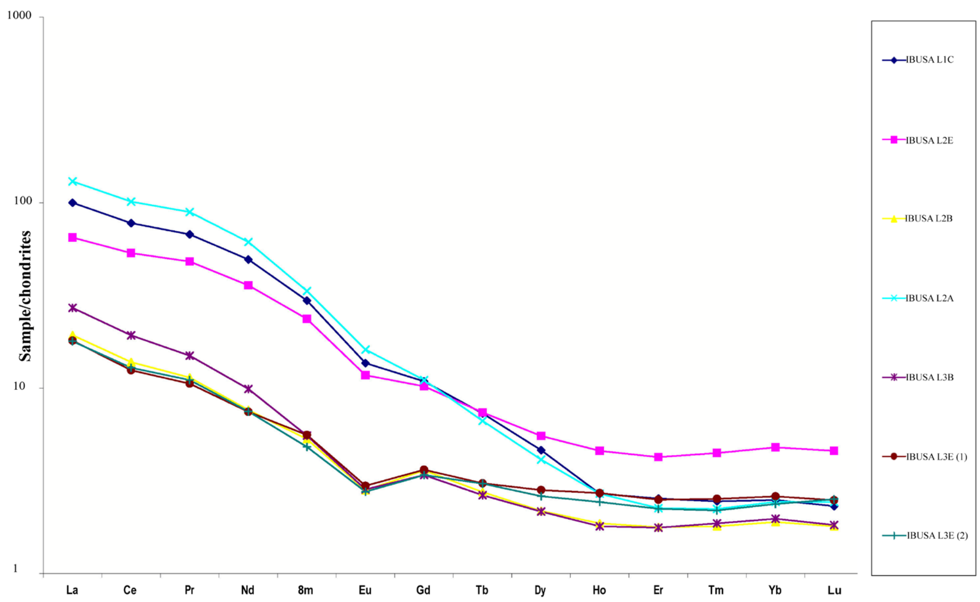

Figure 5. Chondrite normalized REE patterns for sandstones of the Ogwashi-Asaba Formation.

Table 5. Trace element compositions (ppm) and their ratios for sandstone samples obtained from the Ogwashi-Asaba Formation.

Rock type	Ferruginous sandstones			Non-ferruginous sandstones		
Sample #	**IBS_L2E**	**IBS_L3E**	**IBS_L2B**	**IBS_L1C**	**IBS_L2A**	**IBS_L3B**
Sc	4	3	5	3	2	1
Ni	19	18	19	17	18	17
Ga	3	2	8	2	2	3
Nb	10	5	5	7	7	6
Ba	31	11	12	44	48	19
Ta	0.5	<0.1	<0.1	0.1	0.2	0.2
Co	5	2	3	2	1	1
Cu	9	9.5	8.9	9.9	9.6	9.8
Sr	12	5	9	16	17	22
V	46	28	37	18	12	20
Zn	40	<30	<30	<30	<30	<30
Th	3.9	1.3	2.3	2.2	2.1	2.3
U	3.7	2.8	3.4	1.8	1.3	0.9
Cr	40	20	40	20	17	30
Rb	1.8	2	1.8	1.6	1.5	1.6
Zr	200	53	54	119	154	84
Hf	4.4	1.2	1.3	2.6	3.4	2.0
Zr/10	20	5.3	5.4	1.19	1.54	8.4
Th/U	1.05	0.46	0.68	1.22	1.62	2.56
Rb/Sr	0.15	0.40	0.20	0.10	0.09	0.07
Cr/Th	10.26	15.38	17.39	9.09	8.10	13.04
Cr/Zr	0.20	0.38	0.74	0.17	0.12	0.36
Th/Sc	0.98	0.43	0.42	0.73	1.05	2.30
Th/Zr	0.020	0.025	0.043	0.018	0.014	0.027
La/Th	5.26	4.38	2.65	14.32	19.57	3.70
Co/Th	1.28	1.54	1.30	0.91	0.48	0.43
La/Sc	5.13	1.90	1.22	10.50	20.55	8.50
La/Co	4.10	2.85	2.03	15.75	41.10	8.50
Th/Co	0.78	0.65	0.77	1.10	2.10	2.30
Th/Cr	0.09	0.07	0.06	0.11	0.11	0.08
Ba/La	1.51	1.93	1.97	1.40	1.17	2.24

Table 6. Rare earth element concentrations (in ppm) for sandstones obtained from the Ogwashi-Asaba Formation.

Rock type	Ferruginous sandstones			Non-ferruginous sandstones		
Sample code	IBS_L2E	IBS_L3E	IBS_L2B	IBS_L1C	IBS_L2A	IBS_L3B
La	20.5	5.7	6.1	31.5	41.1	8.5
Ce	43.5	10.3	11.2	63.1	82.4	15.7
Pr	5.39	1.21	1.28	7.56	9.97	1.67
Nd	21.4	4.5	4.6	29.5	36.6	5.9
Sm	4.5	1.0	1.0	5.7	6.4	1.1
Eu	0.85	0.21	0.20	0.99	1.17	0.21
Gd	2.7	0.9	0.9	2.8	2.9	0.9
Tb	0.4	0.2	0.1	0.4	0.3	0.1
Dy	1.8	0.9	0.7	1.5	1.3	0.7
Ho	0.3	0.2	0.1	0.2	0.2	0.1
Er	0.9	0.5	0.4	0.5	0.5	0.4
Tm	0.14	0.08	0.06	0.08	0.07	0.06
Yb	1.0	0.5	0.4	0.5	0.5	0.4
Lu	0.15	0.08	0.06	0.07	0.08	0.06
Y	7.0	4.0	4.0	5.0	5.0	3.0
Eu/Eu^*	0.69	0.66	0.63	0.67	0.72	0.63
Eu*	1.23	0.32	0.32	1.48	1.63	0.33
ΣLREE	95.29	22.7	24.18	137.36	176.47	32.87
ΣHREE	7.39	3.36	2.72	6.05	5.85	2.72
Σ REE	103.53	26.28	27.10	144.4	183.49	35.8
LREE/HREE	12.89	6.76	8.89	22.70	30.17	12.08

negative Eu anomalies, pointing to the fact that the provenance was mainly continental crustal rocks. The pattern of REE shows appreciable heavy rare earth element (HREE) depletion (a fairly flat HREE pattern).

5. Discussion and Interpretations

5.1. Source-Area Weathering

The Z.T.R. index calculated for the sandstones is a high (66.99%) indicating that they are mineralogically matured [37]. Such level of mineralogical maturity is suggestive of either rapid chemical weathering and erosion in high relief source area or a reworking and recycling of pre-existing older sandstones. The depletion of the alkali and alkali earth element and enrichment of Al_2O_3 is a consequence of the alteration of igneous and metamorphic rocks during chemical decomposition (weathering). Thus following from Nesbitt and Young [45] and Fedo *et al*. [46]; and in order to determine the source area weathering history of the Ogwashi-Asaba sandstones, the Chemical Index of Alteration (CIA) and Chemical Index of Weathering (CIW) for all samples were calculated and values are presented in **Table 4** and **Figure 6**. The CIA values range from 87.7% to 93.3% (average 89.92%) and CIW from 89.4% to 94.7% (average 91.87%) suggestive of the fact that the source region was subjected to intense chemical weathering likely under tropical palaeo-climatic conditions with abundant rainfall. The CIA and CIW values also signify a dominant felsic source and sediment recycling processes [47]. The concentrations of trace elements and REE in the sandstones are indicative of possible sediment weathering, recycling and sorting during transportation and subsequent heavy mineral enrichment. Thus, the high concentrations of Zr and LREE in the sandstones are indices to heavy mineral enrichment in zircon and monazites respectively. The steep

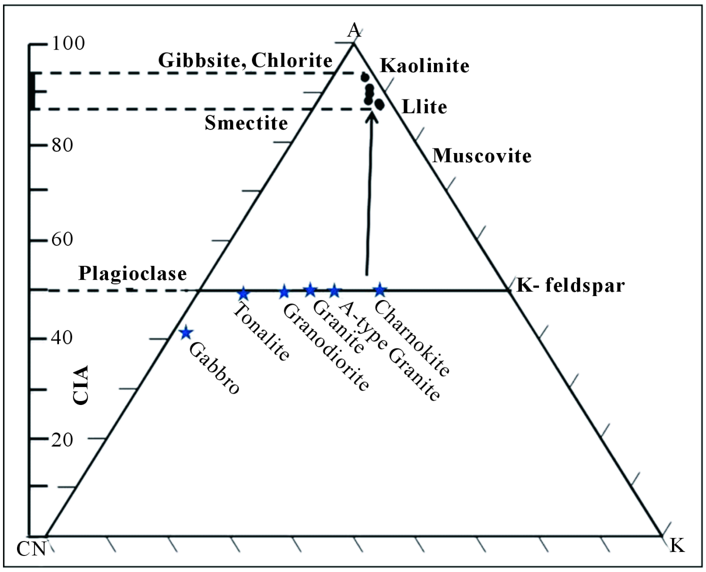

Figure 6. Chemical Index of Alteration (CIA) ternary plot of molecular proportions of Al_2O_3-(CaO^* + Na_2O)-K_2O for sandstones from the Ogwashi-Asaba Formation [4] [45] [46]. The solid arrow shows the actual weathering trend for the samples.

chondrite-normalized REE trend **Figure 6**, especially the unusually high La concentration is a reflection of possible monazite enrichment.

5.2. Provenance

The high percentage of opaque minerals (42%) is attributable to haematite resulting from the ferruginous sand (average 19.11 % Fe_2O_3). The presence of zircon, tourmaline, rutile and the suite of opaque heavy minerals (e.g. haematite) is an indication of sediments derived mostly from reworked sources and partly from felsic or acidic igneous rocks.

Major element compositions of sandstones have also been used to determine sedimentary provenance by the application of discriminant function analysis [48] which distinguishes between four fields of sedimentary provenance, namely: mafic igneous (P1), intermediate igneous (P2), felsic igneous (P3) and quartzose sedimentary or recycled (P4). The sandstones of the Ogwashi-Asaba Formation plot in the P3 and P4 fields, **Figure 7**, indicating mixed source rock (granitic-gneissic or sedimentary) derivation. Furthermore, evidence of passive margin environment of deposition [49] is provided in **Figure 8** which shows major element tectonic setting discriminant function diagram for sandstones of the Ogwashi-Asaba Formation. Finally, the major element tectonic setting discriminant diagram in which Log (K_2O/Na_2O)] is plotted against SiO_2 [50] shows that most of the Ogwashi-Asaba sandstones plot in the passive margin depositional area, **Figure 9**. Passive margin provenance setting consists of recycled sediments that may have been sourced from tectonic uplift of the adjacent sedimentary basins.

Trace elements such as the REE and the high field strength elements (Co, Sc, Hf, Ta, Nb, Ti and Y) are also very useful for provenance studies because of their relatively low mobility during surface sedimentary processes. The negative Eu anomalies shown in **Figure 6** and **Table 6** suggest provenance from materials that have undergone intra-crustal geochemical differentiation involving plagioclase or orthoclase feldspar acting as a residual phase. The Eu/Eu* values obtained averaged 0.67, which falls within characteristic range of Post Archean Sediments [39].

When elemental ratios from the sandstones of the Ogwashi-Asaba Formation are compared with those described by Condie [40], Armstrong-Altrin *et al.* [11], Osae *et al.* [44] and those from other areas (**Table 7**), the ratios La/Sc, Th/Sc, Cr/Th, and Eu/Eu* fall within the range of felsic sources and upper continental crust (UCC). Furthermore, the La/Sc, Th/Sc, La/Co, Th/Co, Th/Cr, and Eu/Eu* ratios correspond with similar fractions obtained from felsic and mafic rocks described by Cullers and Podkovyrov, [43] and UCC as described by Taylor

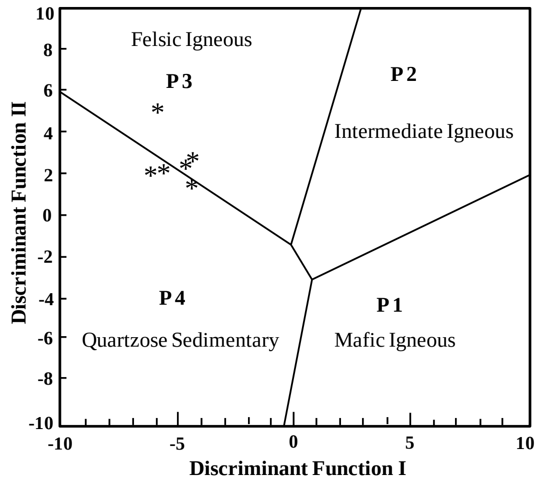

Figure 7. Discriminant function diagram for provenance of the sandstones obtained from the Ogwashi-Asaba Formation.

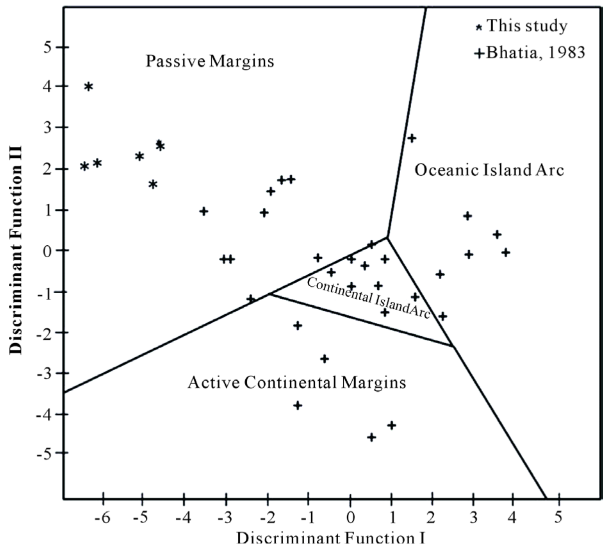

Figure 8. Major element tectonic setting discriminant function diagram for sandstones obtained from the Ogwashi-Asaba Formation.

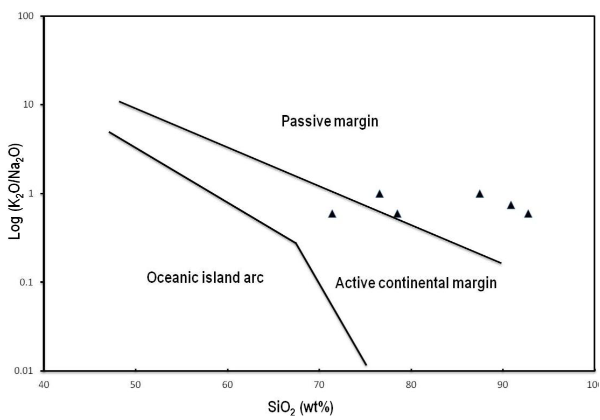

Figure 9. Major element tectonic setting discriminant diagram [Log (K_2O/Na_2O)] versus SiO_2 for sandstones of the Ogwashi-Asaba Formation.

Table 7. Range of elemental ratio of sandstones from Ogwashi-Asaba compared to the ratio in average Proterozoic sandstones, upper continental crust and sandstone derived from felsic rocks and mafic rocks.

Elemental ratio	Range of Ogwashi-Asaba sandstone[a]	Range of sediments from felsic sources[b]	Range of sediments from mafic sources[b]	Average Proterozoic sandstones[c]	Upper continental crust (1.6 - 0.8 Ga)[c]	Range of Buem sandstone, Ghana[d]
La/Sc	1.22 - 20.55	2.50 - 16.3	0.43 - 0.86	4.21	1.91	1.70 - 12.1
Th/Sc	0.42 - 2.30	0.84 - 20.5	0.05 - 0.22	1.75	0.71	0.53 - 1.82
Cr/Th	8.10 - 17.39	4.00 - 15.0	25.0 - 500	5.71	4.46	5.74 - 21.1
Eu/Eu*	0.63 - 0.72	0.40 - 0.94	0.71 - 0.95	0.67	0.59	0.60 - 1.09

[a]This study; [b][11]; [c][40]; [d][44].

Table 8. Range of elemental ratios of Ogwashi-Asaba sandstone compared with ratios in similar fractions derived from felsic and mafic rocks [43] and upper continental crust [39].

Elemental ratio	Range of Ogwashi-Asaba sandstone	Range of sediments from felsic sources	Range of sediments from mafic sources	Upper continental crust
Eu*	0.32 - 1.63	0.40 - 0.94	0.71 - 0.95	0.63
La/Sc	1.22 - 20.55	2.50 - 16.3	0.43 - 0.86	2.21
Th/Sc	0.42 - 2.30	0.84 - 20.5	0.05 - 0.22	0.79
La/Co	2.03 - 41.10	1.80 - 13.8	0.14 - 0.38	1.76
Th/Co	0.65 - 2.30	0.67 - 19.4	0.04 - 1.40	0.63
Th/Cr	0.06 - 0.11	0.067 - 4.0	0.002 - 0.045	0.13

and McLennan [39] (**Table 8**).

The REE results, **Table 6** also show Eu* values that are attributable to felsic sources with some input from a mafic source and an UCC. This is also supported by the Cr/Zr ratios [51] which as shown in **Table 5** are all below unity and thus indicative of felsic sources.

5.3. Tectonic Setting

Roser and Korsch [50] identified three tectonic settings namely, a passive continental margin (PM), active continental margin (ACM) and oceanic island arc (ARC) on a K_2O/Na_2O-SiO_2 discrimination diagram, **Figure 9** on which sandstone samples from the Ogwashi-Asaba Formation plot mostly in the PM field with some overlap into the ACM field. PM sediments are usually quartz rich sediments sourced from stable continental areas or intra-plate regions and deposited in intra cratonic basins or passive continental margins.

6. Conclusion

Heavy mineral data from sandstone layers of the Ogwashi-Asaba Formation show that they are mineralogically mature and derived from both reworked sedimentary and felsic rock sources. Geochemical data also provide indications of the possible palaeo-climate and ancient weathering conditions of the source area, provenance and tectonic setting of deposition. The sandstones are SiO_2 and Fe_2O_3 rich. CIA and CIW values indicate that the source region was subjected to intense tropical weathering in warm tropical climate. Provenance discrimination diagrams also support the interpretation that the source area was dominated by felsic igneous and recycled sediments. Concentrations of major and trace elements suggest a passive margin setting. It may thus be concluded that the sandstones of the Ogwashi-Asaba Formation were likely derived from the SW and SE Basement Complex rocks (granites, gneisses, etc.) and sedimentary fills of the adjacent basin (Anambra basin and the Benue Trough).

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