Ilorin Journal of Science
Volume 2, Number 1, 2015, pp. 163 – 189 (Printed in Nigeria)
ISSN: 2408 – 4840 © 2015 Faculty of Physical Sciences, University of Ilorin
https://doi.org/10.54908/iljs.2015.02.01.012

ILORIN
JOURNAL OF SCEINCE

ILJS-14-057

Combined Petrographic and Geochemical Studies of Maastrichtian Patti Formation Sandstone, Bida Basin, Nigeria: Implications for Provenance and Compositional Maturity

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Abstract

Geochemical data on sandstone facies of the Maastrichtian Patti Formation in Bida Basin, Nigeria, is presented and interpreted in this paper with respect to its provenance and compositional maturity. Petrographic data from thin sections and X-Ray Diffractometry were also integrated. Petrographic data from the sandstones classified them mainly as quartz-arenites and minor sub-arkose while geochemical indices such as high average values of SiO_2/Al_2O_3, low Na_2O+K_2O and K_2O/Na_2O values also indicate the samples are sub-litharenite to quartz-arenite type. Relatively high average values of total REE (141.40 ppm), Th (7.59 ppm), Hf (6.82 ppm), and Zr (205.12 ppm) coupled with low concentrations of Ni (3.06 ppm), Co (1.66 ppm) and V (20.65 ppm) in the sandstones indicate felsic igneous provenance. The discrimination functions plot shows that the sandstones were sourced mainly from matured sedimentary provenance and a passive margin setting is deducted based on the plots of TiO_2 versus Fe_2O_3+MgO and K_2O/Na_2O versus SiO_2. The sandstones show high average value of SiO_2 (86.8 %) and low values of Al_2O_3 (6.11 %), K_2O (0.12) and Na_2O (0.02 %), suggesting that the sediments are mature. Plot of SiO_2 versus ($Al_2O_3+K_2O+Na_2O$) further lend credence to chemical maturity and reveals semi-humid to humid paleoclimate. The Chemical Index of Alteration (CIA) value of 96.49 and the Plagioclase Index of Alteration (PIA) of 99.05 respectively are supportive of high weathering of the source area. The sands were most probably recycled from older Lokoja Formation during the late Maastrichtian Tethys inundation in the basin.

Keywords: Agbaja, humid, maturity, Patti, plagioclase, provenance

1. Introduction

Geochemistry of clastic sediments is of great significance in basin analysis. In the last three decades, geochemical data have become increasingly a valuable tool for characterizing and unraveling the provenance of sedimentary rocks. Notable successes recorded in this line include the pioneer efforts of Bhatia (1983) and McLennan *et al.* (1983).

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The relationship between composition of sandstones and sedimentary processes such as weathering, source rock, erosion and transportation was examined and a strong linkage established (Dickinson and Suczek, 1979; Dickinson *et al.*, 1983). The application of geochemical data is largely a complement to basic petrographic data which reveals among other things provenance, sediments maturity and paleotectonic province.

Recent work of Ojo and Akande (2009) has drawn attention to the depositional characteristics and model of the sandstone facies of the Maastrichtian Patti Formation in the intracratonic Bida Basin of Nigeria (Fig. 1). They attempted to emphasize the need to recognize and distinguish the Patti Formation as a mappable entitity with distinct sedimentological characteristics within the context of streamlining and refining the stratigraphic framework of the basin (Ojo and Akande, 2006, 2008). Akande *et al.* (2005) also examined the source rock characteristics of the shale facies of the Patti Formation and noted its gas potential as a source rock. At present, aspect of the geochemical characterization of the Patti sandstones is lacking.

The present work is motivated by the need to further understand the peculiar compositionally characteristics and provenance of these sandstones which its close proximity to the potential source rock may present petroleum system in the largely unexplored basin in Nigeria. The paper therefore provides the first comprehensive geochemical characteristics, weathering history, source rock type and maturity of the Maastrichtian tidal to shoreface sandstones in the Bida Basin. The applicability of geochemical indices in provenance and depositional setting reconstruction of Upper Cretaceous sediments in rift basins is also demonstrated.

2. Geological Setting of the Bida Basin

Among the hinterland sedimentary basins in Nigeria is the Bida Basin (also refer to as Nupe and Niger Basin) which is located in the central, western part of Nigeria. It is an intracratonic shallow depression filled with estimated 3500m thick clastics (Udenzi and Ozasuwa, 2004) and trends northwest southeast. The southeastern part of the basin which is the focus of the present study is located near the confluence of Niger and Benue rivers (Fig. 1).

The geological framework in terms of evolutional model and structural pattern has been presented in many published works. These include the work of King (1950) and Kennedy (1965) who interpreted the basin as rift bounded tensional structure and a product of rifting and faulting associated with the larger Benue Trough system, during the early Cretaceous separation of Africa and South America plates. The findings of other related studies (Ojo and

Ajakaiye, 1989; Kogbe *et al.*, 1983) which include identification of NW/SE trending faults and existence of deep seated central positive anomaly flanked by negative anomalies respectively are in congruence with rift theory.

On the other hand, Adeleye (1976) and Whiteman (1982) suggested the idea of simple post Santonian cratonic sag and Braide (1992) identified sinistral movements based on which he proposed a pull apart origin. The basin is adjacent and almost perpendicular to the Benue Trough popularly believed to have evolved consequent upon break up and separation of Brazilian and African plates in the Early Cretaceous time. Only late Cretaceous sediments have been recorded in the Bida Basin which correlates with the late Cretaceous sediments in the Benue Trough (Anambra basin). Often the Bida Basin is regarded as northwestern extension of Anambra Basin (Akande *et al.*, 2005).

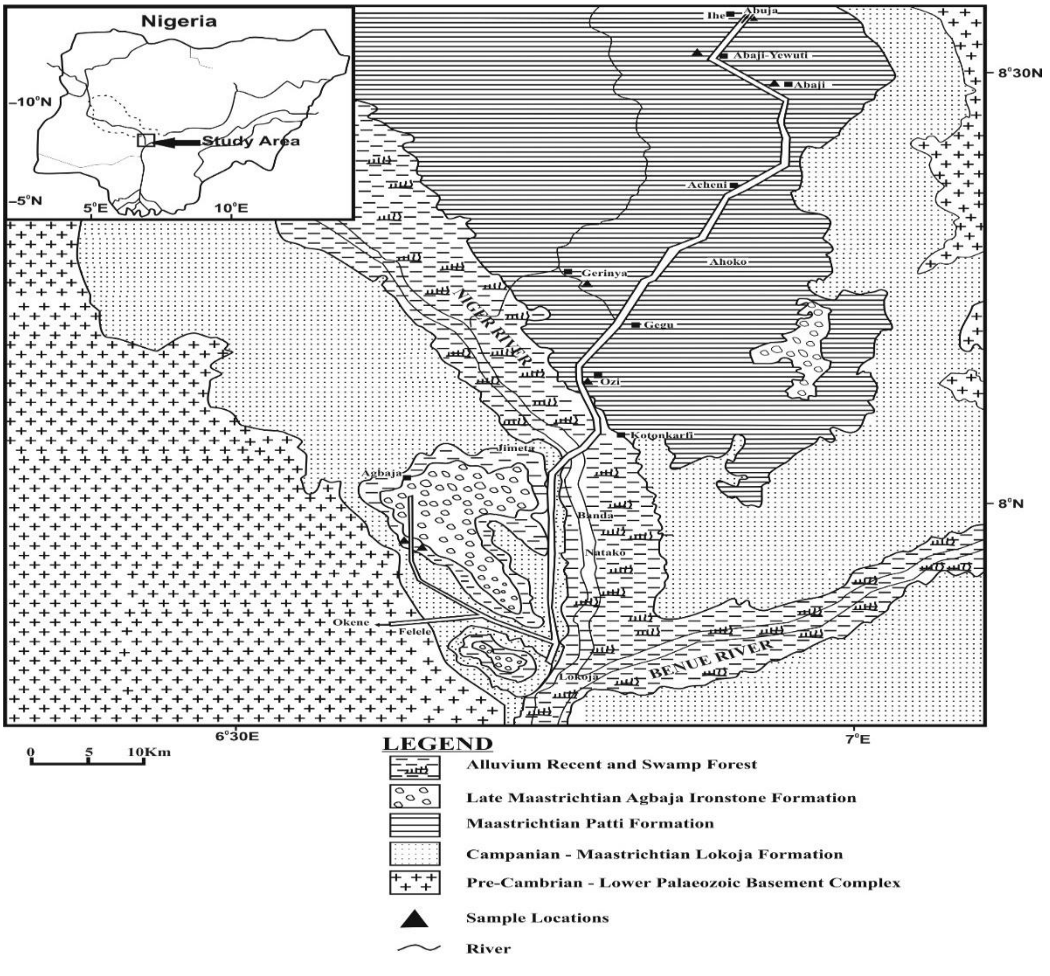


Fig.1: Geological map of southern Bida Basin and sample locations. Inset is the map of Nigeria (modified after Ojo and Akande, 2009).

The stratigraphic framework of the Upper Cretaceous Bida Basin has received attention of several workers among which is the work of Adeleye and Dessauvagie (1972) and Adeleye (1974). For ease of stratigraphic delineation, they subdivided the basins into two arms; northern and southern Bida basins each with distinct mappable stratigraphic entities. Agyingi (1993) and Ojo and Akande (2006, 2008) presented a detail description of the stratigraphic succession in the southern Bida Basin. The oldest unit in the southern Bida Basin is the Campanian Lokoja Formation which consists mainly of alluvial to fluvial channel sandstones and minor claystones (Ojo and Akande 2003). It is a stratigaphic equivalent of the Bida Formation in the northern Bida Basin (Fig. 2). This is succeeded by the Maastrichtian Patti Formation, which is the focus of the present investigation. The Patti Formation was deposited in a wide range of environments ranging from shoreface, tidal channel, tidal marsh to coastal swamp. The shoreface and tidal facies association comprises of well sorted, fine to medium grained sandstone and minor coarse to very coarse grained sandstone (Ojo and Akande, 2009).

In this study, samples of the shoreface and tidal channel facies were selected for geochemical and petrographic investigations. The swamp to marsh facies of the Patti Formation is represented by shale and clay rich lithologies. The lateral equivalent of the Patti Formation in the northern Bida Basin is the Enagi Formation. The Agbaja Formation which is the lateral equivalent of the Batati ironstone in the north capped the entire sequence and the probable age is late Maastrichtian. Correlation of the stratigraphic successions across the northern and the southern parts of the basin to is largely based on the lithologic and depositional characteristics and has been extended into the Anambra Basin to the south (Fig. 2). These lateral equivalents represent continuous depositional phases from the south to the north and northwest, controlled by the major sea level rise and falls of the Upper Cretaceous.

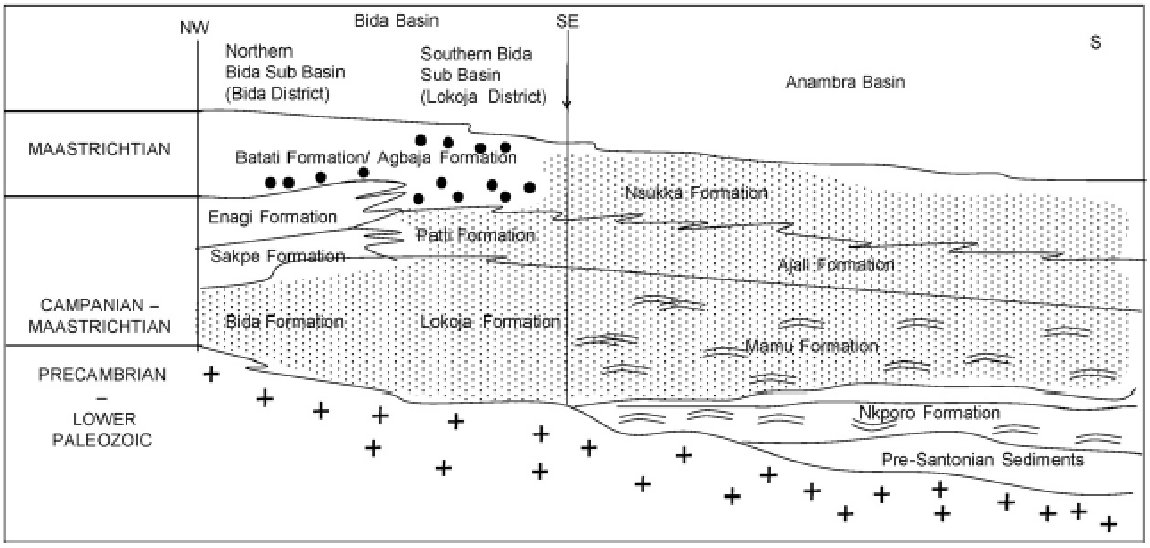


Fig. 2: Regional stratigraphic successions in the Bida Basin and stratigraphic relationships to the Anambra Basin (Ojo and Akande, 2009).

3. Materials and Methods

The logging and sampling exercise was carried out along the following traverses Lokoja-Agbaja, Gegu – Gerinya, Kotonkarifi - Abuja, where the sandstone facies of the Patti Formation outcropped (Fig. 1). Thin sections of eighteen sandstone samples were prepared for petrographic study and studied using petrological microscope at the Department of Geology and Mineral Sciences, University of Ilorin, Nigeria. The mineralogy was complemented by X-Ray Diffraction (XRD) analysis performed on six samples at the University of Pretoria, South Africa. The samples were selected for elemental composition (major, trace and rare earth elements REE) analyses through X-Ray Fluorescence (XRF) and Inductively Coupled Plasma Emission Spectrometry (ICPMS) at ACME laboratory, Canada.

4. Results and Discussion

4.1 Mineral Composition

Results of the thin section microscopy show quartz as the dominant mineral in the samples (Table 1). Monocrystalline quartz type predominates over the polycrystalline type in most of the samples. They constitute between 90.5 to 100% of the framework component. Feldspar is rare to absent in the studied sandstones, occurring less than 7% in most of the samples. Potassium feldspar is more than the plagioclase. Rock fragment is absent in most samples and where present it is less than 5% of the framework components. Matrix is however relatively high ranging from 4 to 16% of the whole rock. In the Abaji samples, the modal percentage matrix is higher than the average of all the samples.

The clay minerals which constituted most of the matrix were separated and examined with XRD. The dominant clay mineral is kaolinite and minor amount of montmorillonite is recorded. Non-clay minerals include; quartz, zircon, goethite and muscovite.

Tab.1: Modal analysis and framework composition of the Patti Formation sandstones

Location	Sample No	% Quartz			% Feldspar			Mica	R.F	Matrix	Cement	Framework Composition		
		MQ	PQ	TQ	M	P	TF					Q	F	R.F
Gerinya	GER2A	45	40	85	-	-	-	2	1	7	5	98.8	-	1.2
Gerinya	GER2E	50	38	88	-	-	-	5	-	5	2	100	-	-
Gerinya	GER2G	48	30	78	2	-	2	4	1	7	7	96.3	2.5	1.2
Agbaja	AGB1J	52	35	87	-	-	-	3	1	6	3	98.9	-	1.1
Agbaja	AGB1S	60	30	90	-	-	-	5	-	4	1	100	-	-
Agbaja	GB1E	37	36	63	5	8	13	7	4	9	4	78.7	16.3	5.0
Agbaja	GB1H	48	37	85	3	-	4	4	-	4	3	95.5	4.5	-
Agbaja	GB1L	46	40	86	-	-	-	5	-	5	4	100	-	-
Abaji	ABJ1A	40	26	66	4	1	5	7	2	14	6	90.5	6.8	2.7
Abaji	ABJ1D	39	33	72	1	-	1	5	3	16	3	94.7	1.3	4.0
Abaji	ABJ1F	44	30	74	2	1	3	6	-	10	10	96.1	3.9	-
Abaji	ABJ1K	48	35	83	2	-	2	7	1	5	2	97.6	2.4	-
Abaji-Yewuti	GD2A	46	27	73	-	3	3	6	-	15	3	96.1	3.9	-
Abaji -Yewuti	GD2G	45	24	69	-	-	-	10	-	16	5	100	-	-
Abaji -Yewuti	GD2K	45	30	75	1	-	1	7	1	9	7	97.4	1.3	1.3
Ozi	BB1A	49	29	78	2	1	3	2	1	5	11	95.1	3.7	1.2
Ozi	L7D	51	35	86	1	-	1	3	-	6	4	98.9	1.1	-
Ihe	EJ1A	47	33	80	-	-		5	-	12	3	100	-	-
Ihe	EJ1B	48	41	89	-	-	-	1	-	8	2	100	-	-

NB: Q-quartz, f-Feldspar, MQ-monocrytalline quartz, PQ-polycrstalline quartz, TQ-total quartz, M-miccrocline, P-plagioclase, TF-total feldspar, R.F-rock fragment.

4.2 Major, Trace and Rare Earth Element Composition

The SiO_2 of the Patti Formation samples is relatively ranging between 76.3 to 95.8% with exception of sample BB1A from Ozi with 56.4% and very high Fe_2O_3 of 35.18% (Table 2). The sandstone samples from the Agbaja and Ihe sections have higher SiO_2 content than the samples from other locations at Ozi, Gerinya and Abaji. This is significant because the Agbaja section is essentially a road section cutting through a flat top northeast southwest trending ridge of about 300m relief. Other sections are located in the relatively low lying area. The exceptional high amount of Fe_2O_3 in sample BB1A from Ozi, was most probably due to late ferruginization, considering its proximity to ironstone beds. Iron rich water draining the overlying ironstones might have permeated the bed and consequently enhanced oxidative process. Al_2O_3 content is low in all the samples ranging from 2.0 to 14.57% and averaging 6.19%. However, Al_2O_3 is relatively high in the Abaji samples and this is a likely reflection of the substantial clay matrix of the sands.

Generally, the sandstones are depleted in other major oxides notably among which are MgO, CaO, K_2O and Na_2O. This trend may be attributed to intense weathering and alteration of feldspars and unstable mafic minerals (Getaneh, 2002; Zhang, 2004). There is higher amount of Na_2O and K_2O in samples from Gerinya, Ozi and Abaji than Ihe and Agbaja localities due to variation in compositional maturity. K_2O is higher than Na_2O in most samples except those from Agbaja, in deed, average ratio of K_2O/Na_2O is high (8.39) indicating more of potassium feldspar than plagioclase according to Nath *et al.*, (2000). The low amount of MgO, CaO, and MnO shows that the environment is siliciclastic and non-carbonate (Glasby, 1977). The ratio of TiO_2/Al_2O_3 varies from 0.02 to 0.12% (Table 3). It is highest at Ihe and Agbaja sections and lowest at Gerinya, a similar trend with K_2O and Na_2O in the locations.

Tab.2: Major elements (%), CIA and PIA values of the Patti Formation sandstones

	Sample no.	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**TiO_2**	**MnO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**MgO**	**CIA**	**PIA**
1	**GER2A**	89.6	5.89	0.87	0.31	0.009	0.03	0.009	0.05	0.01	0.03	97.19	99.34
	GER2E	90.5	5.60	1.15	0.22	0.009	0.03	0.009	0.08	0.01	0.03	96.55	99.30
	GER2G	88.6	4.18	4.52	0.09	0.01	0.02	0.009	0.09	0.01	0.02	97.23	99.30
2	**AGB1J**	92.0	3.58	1.38	0.15	0.009	0.009	0.009	0.01	0.01	0.009	99.22	99.50
	AGB1S	95.2	2.20	0.44	0.26	0.009	0.009	0.009	0.009	0.01	0.009	98.79	99.19
	GB1H	94.0	3.73	0.81	0.18	0.009	0.02	0.009	0.009	0.02	0.009	98.99	99.23
	GB1L	95.8	2.00	0.51	0.15	0.009	0.06	0.05	0.009	0.01	0.009	94.38	94.76
3	**ABJ1A**	76.3	14.57	1.57	0.36	0.009	0.05	0.009	0.12	0.009	0.02	98.79	99.59
	ABJ1D	81.8	10.22	1.76	0.64	0.009	0.03	0.009	0.07	0.03	0.01	98.94	99.62
	ABJ1F	80.5	12.93	0.86	0.22	0.009	0.02	0.009	0.07	0.01	0.009	99.24	99.78
	ABJ1K	91.0	5.33	0.69	0.26	0.009	0.009	0.009	0.03	0.02	0.009	99.11	99.66
4	**EJ1A**	95.6	2.18	0.69	0.12	0.01	0.009	0.009	0.009	0.009	0.009	98.78	99.18
	EJ1B	94.7	2.35	0.80	0.34	0.01	0.009	0.009	0.01	0.009	0.009	98.82	99.24
5	**GD2A**	81.4	10.88	1.65	0.46	0.01	0.04	0.009	0.11	0.02	0.02	98.56	99.55
	GD2G	83.8	9.16	2.69	0.23	0.009	0.02	0.009	0.05	0.03	0.01	99.14	99.68
	GD2K	88.9	6.36	1.10	0.22	0.009	0.05	0.009	0.05	0.05	0.009	98.32	99.07
6	**BB1A**	56.4	2.18	35.18	0.14	0.02	0.01	0.01	0.61	0.02	0.009	77.58	99.87
	L7D	85.5	6.56	2.07	0.49	0.12	0.03	0.17	0.77	0.05	0.05	87.12	97.10
	Mean	86.8	6.11	3.26	0.27	0.016	0.025	0.02	0.12	0.02	0.016	96.49	99.05

Location of study

1. **Gerinya**
2. **Agbaja**
3. **Abaji**

4. **Ihe**
5. **Abaji - Yewuti**
6. **Ozi**

Rollinson (1993) described trace elements as those that are present in any rock at less than 0.1% and their concentration are expressed in part per million of the element. The most useful and important trace elements are those immobile in sedimentary cycle such as Ce, La, Ti, Ta, Th, Co, Ni, Sc, Zr, Hf, Nb and they show low residence time in sea water (Holland, 1986; Bhatia and Crook, 1986). They are suitable for provenance and tectonic setting determinations. The distribution of the trace elements varies across the study area (Table 4). The ferromagnesian trace elements (Co and Ni) composition of the Patti Sandstones is generally low but higher in Gerinya, Ozi and Abaji than at Agbaja and Ihe. The trend is same with the SiO_2 variation in the locations. Also the mobile elements, which include (Cs, Sr, K, Rb and Ba) are relatively depleted in the Patti Formation (Table 4). This observation may be linked to low proportion of the unstable mafic minerals in the sandstone facies of the Patti Formation and gradual leaching of these elements during transportation history of the Patti sediments.

Across the study locations, nickel (Ni) varies from 0.70 to 3.70 ppm (except in Ozi samples with average of 8ppm). Its depletion may be due to the reworking and recycling during sedimentary process. The observed depletion in strontium (Sr) in the samples probably reflects dissolution of feldspar and the recycling of feldspar with increasing maturity (Das *et al*., 2006; Dey *et al*., 2009). Sr and Ba are however very high in samples from Abaji and Ozi samples. Interestingly, there is corresponding low amount of immobile Zr and Hf in the samples from these areas. Present day topography may have induced rapid dissolution and leaching in the Agbaja and Ihe areas than Abaji, Ozi and Gerinya.

The Rare Earth Elements (REE) comprises of metals with atomic number 57-71 and these include; La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Er, Tm, Yb and Lu. These elements are classified as the least soluble trace elements and are relatively immobile during weathering, diagenesis, low-grade metamorphism and hydrothermal alterations (Michard, 1989). REE is a vital geological tool for determining provenance. They are typically transferred unfractionated into sediments and hence reflect the average REE composition of the source (Feng and Kerrich, 1990; Taylor and McLennan, 1985). The total and average values of rare earth elements (REE), light rare earth elements (LREE), heavy rare earth elements (HREE), europium anomaly and their mean values in the investigated sandstones are presented in table 5. The average total REE of the samples, 141.40 ppm is less than that of PAAS (184.77) and NASC (154.48) and UCC (146.37) (Table 5).

The chondrite normalized REE distribution (Fig. 3) shows LREE enrichment and displayed similarity with UCC and slightly depleted relative to PAAS and NASC. In the Patti Formation sandstones, the REE is low (∑REE 33.45 – 970.5). There is also an enrichment of light LREE, (∑LREE 2.67 – 356.5) over the heavy REE (∑HREE 2.59 – 576.1). A pronounced negative Europium anomaly (EU/EU*) of 0.21 – 1.87 (average of 1.11) is observed. EU/EU* less than one is obtained from all the samples except the Abaji samples where high total REE values and extremely low LREE/HREE were recorded. The chondrite normalized diagram also revealed a steep LREE and relatively flat HREE. Generally, the REE (HREE in particular) contents of the Patti Formation differ slightly from that of North America Shale Composite (NASC) and Upper Continental Crust (UCC) (see table 6).

Tab. 3: Values of ratios of some major elements and geochemical indicators of the sandstones

Elements/Sample ID	**GER2A**	**GER2E**	**GER2G**	**AGB1J**	**AGB1S**	**GB1H**	**GB1L**	**ABJ1A**	**ABJ1D**	**ABJ1F**	**ABJ1K**	**EJ1A**	**EJ1B**	**GD2A**	**GD2G**	**GD2K**	**BB1A**	**L7D**	**Mean**
K_2O/Na_2O	5.56	8.89	10.00	1.11	1.00	1.00	0.18	13.33	7.78	7.78	3.33	1.00	1.11	12.22	5.56	5.56	61.00	4.50	8.39
Na_2O+K_2O	0.059	0.089	0.099	0.019	0.018	0.018	0.059	0.129	0.079	0.079	0.039	0.018	0.019	0.119	0.059	0.059	0.62	0.94	0.14
$CaO+Na_2O$	0.039	0.039	0.029	0.018	0.018	0.029	0.11	0.059	0.039	0.029	0.018	0.018	0.018	0.049	0.029	0.059	0.02	0.20	0.045
$Al_2O_3/(CaO+Na_2O)$	151.03	143.59	144.14	189.89	122.22	128.62	18.18	246.95	262.05	445.86	269.11	121.11	130.56	222.04	315.86	107.80	109.00	32.80	177.60
SiO_2/Al_2O_3	15.21	16.16	21.20	25.70	43.27	25.20	47.90	5.24	8.00	6.23	17.07	43.85	40.30	7.48	9.15	13.98	25.87	13.03	21.38
Na_2O/K_2O	0.180	0.113	0.10	0.90	1.00	1.00	5.56	0.075	0.129	0.129	0.30	1.00	0.90	0.08	0.18	0.18	0.017	0.22	0.67
TiO_2/Al_2O_3	0.053	0.039	0.022	0.042	0.118	0.048	0.075	0.025	0.063	0.017	0.049	0.055	0.145	0.042	0.025	0.035	0.064	0.075	0.055
Fe_2O_3/Al_2O_3	0.148	0.205	1.081	0.385	0.20	0.217	0.255	0.108	0.172	0.067	0.129	0.317	0.340	0.152	0.294	0.173	16.138	0.316	1.150
Fe_2O_3/ K_2O	17.40	14.38	50.22	138.00	44.00	81.00	51.00	13.08	25.14	12.29	23.00	69.00	80.00	15.00	53.80	22.00	57.67	2.69	42.76
Fe_2O_3+MgO	0.90	1.18	4.54	1.39	0.45	0.82	0.52	1.59	1.77	0.87	0.70	0.70	0.81	1.67	2.70	1.11	35.19	2.12	3.280
K_2O/Al_2O_3	0.008	0.014	0.022	0.003	0.004	0.002	0.005	0.008	0.007	0.005	0.006	0.004	0.004	0.01	0.005	0.008	0.280	0.117	0.029
$Al_2O_3+K_2O+Na_2O$	5.95	5.69	4.28	3.60	2.22	3.75	2.06	14.70	10.30	13.01	5.37	2.20	2.37	11.00	9.22	6.42	2.80	7.50	6.25
$\{Fe_2O_3+MgO\}/\{Na_2O+K_2O\}$	23.08	30.26	156.55	77.17	24.94	28.24	4.72	26.95	45.38	29.97	38.83	38.83	44.94	34.08	93.10	18.80	1759.45	10.60	138.11
$\log(SiO_2/Al_2O_3)$	1.18	1.21	1.33	1.41	1.64	1.40	1.68	0.72	0.90	0.79	1.23	1.64	1.61	0.87	0.96	1.15	1.41	1.11	1.24
$\log(Fe_2O_3/K_2O)$	1.24	1.16	1.70	2.14	1.64	1.91	1.71	1.12	1.40	1.09	1.36	1.84	1.90	1.18	1.73	1.34	1.76	0.43	1.48
$\log(K_2O/Na_2O)$	0.75	0.95	1.00	0.05	0.00	0.00	-0.74	1.12	0.89	0.89	0.52	0.00	0.05	1.09	0.75	0.75	1.79	0.65	0.58
$\log(Na_2O/K_2O)$	-0.74	-0.95	-1.00	-0.05	0.00	0.00	0.75	-1.12	-0.89	-0.89	-0.52	0.00	-0.05	-1.10	-0.74	-0.74	-1.77	-0.67	-0.58
$\log(\{Fe_2O_3+MgO\}/\{Na_2O+K_2O\})$	1.36	1.48	2.19	1.89	1.40	1.45	0.67	1.43	1.66	1.48	1.59	1.59	1.65	1.53	1.97	1.27	3.25	1.03	1.61

Tab. 4: Trace element concentration (ppm) in the Patti Formation Sandstone

Elements/ID	**Ba**	**Co**	**Hf**	**Nb**	**Rb**	**Sr**	**Ta**	**Th**	**U**	**V**	**Zr**	**Ni**	**Th/U**	**Th/Co**	**Rb/Sr**	**Ba/Rb**	**Zr/Hf**	**Zr/Nb**	**Zr/Th**	**La/V**	**Zr/TiO_2**
GER 2A	39	1.4	12.3	6.4	2.3	4.5	0.6	10.5	2.7	13	465.5	1.0	3.89	7.5	0.51	16.96	37.85	72.73	44.33	1.42	0.15
GER 2E	41	0.6	3.9	5.4	3.2	8.1	0.6	5.1	1.1	16	141.5	1.1	4.64	8.5	0.40	12.81	36.28	26.20	27.75	0.82	0.06
GER 2G	27	1.7	1.2	2.0	4.9	5.1	0.2	3.3	1.6	17	42.8	3.4	2.06	1.94	0.96	5.51	35.67	21.4	12.97	0.49	0.05
AGB 1J	15	1.5	4.2	2.5	0.5	5.4	0.2	2.6	0.9	14	158.7	0.9	2.89	1.73	0.09	30.0	37.79	63.48	61.04	0.97	0.11
AGB 1S	10	0.6	12	4.2	0.3	8.0	0.4	3.6	1.2	15	488	0.7	3.0	6.0	0.04	33.33	40.67	116.19	135.56	1.01	0.19
GB1 H	18	1.3	3.8	3.4	0.4	10.0	0.2	4.1	0.9	20	139.5	1.5	4.56	3.15	0.04	45.0	36.71	41.03	34.02	0.73	0.08
GB1 L	10	1.4	4.1	2.3	0.2	6.4	0.2	1.9	0.5	11	150.1	1.5	3.8	1.36	0.03	50.0	36.61	65.26	79.0	0.47	0.10
ABJ1A	71	1.8	7.2	9.7	5.0	14.1	0.5	8.9	2.7	33	262.6	1.1	3.30	4.94	0.35	14.2	36.47	27.07	29.51	0.98	0.09
ABJ1D	92	1.6	17.8	12.2	5.3	15.1	0.9	23	4.2	48	694.7	1.3	5.48	14.38	0.35	17.36	39.03	56.94	30.20	1.10	0.11
ABJ1F	54	1.1	3.0	5.4	3.7	13.9	0.3	5.5	1.4	28	122.5	0.9	3.93	5.0	0.27	14.59	40.83	22.69	22.27	0.26	0.06
ABJ1K	45	1.3	3.4	5.2	1.0	32.2	0.3	11.8	1.3	19	123.5	1.4	9.08	9.08	0.03	45.0	36.32	23.75	10.47	1.41	0.05
EJ1A	14	1.2	3.3	2.7	0.2	6.7	0.2	2.7	0.5	7.9	137.7	3.0	5.4	2.25	0.03	70.0	41.73	51.0	51.0	0.61	0.11
EJ1B	17	1.4	10.7	6.3	0.5	4.9	0.5	7.3	0.9	10	425.3	3.4	8.11	5.21	0.10	34.0	39.75	67.51	58.26	0.09	0.13
GD2A	67	1.4	7.7	8.8	5.3	9.2	0.6	12.2	2.1	17	292.1	3.0	5.81	8.71	0.58	12.64	37.94	33.19	23.94	0.23	0.06
GD2G	47	1.0	3.9	4.0	2.6	14.8	0.4	8.6	2.0	45	150.4	2.2	4.3	8.6	0.18	18.08	38.56	37.6	17.49	0.01	0.02
GD2K	210	1.0	1.5	4.0	2.3	105.7	0.3	3.4	0.8	7.9	65.9	2.3	4.25	3.4	0.02	91.30	43.93	16.48	19.38	0.34	0.03
BB1A	171	8.5	2.9	2.1	12	16.6	0.2	2.4	0.9	7.9	116.4	16.3	2.67	0.28	0.72	14.25	40.14	55.43	48.5	0.06	0.08
L7D	221	1.0	19.8	8.0	24	41	0.9	19.8	5.2	42	795	10.0	3.81	19.80	0.59	9.21	40.15	99.38	40.15	0.96	0.32
Mean	64.94	1.66	6.82	5.26	4.09	17.87	0.42	7.59	1.72	20.65	265.12	3.06	4.50	6.21	0.29	29.68	38.69	49.85	41.44	0.66	0.10

Tab. 5: Rare Earth Element concentration (ppm) in the Patti Formation Sandstone

Element/ SAMPLE NO	**GER2A**	**GER2E**	**GER2G**	**AGB1J**	**AGB1S**	**GB1H**	**GB1L**	**ABJ1A**	**ABJ1D**	**ABJ1F**	**ABJ1K**	**EJ1A**	**EJ1B**	**GD2A**	**GD2G**	**GD2K**	**BB1A**	**L7D**	**Mean**
La	18.50	13.10	8.40	13.60	15.10	14.60	5.20	32.5	52.7	7.4	26.7	4.78	0.91	3.98	0.51	2.72	0.49	40.4	14.53
Ce	55.40	28.30	15.40	25.80	31.10	31.60	10.30	47.7	95.5	11.31	44.4	8.02	1.35	7.25	1.05	6.77	1.29	78.2	27.82
Pr	3.81	1.84	1.41	2.50	3.19	3.29	1.00	31.8	51.2	6.92	26.5	4.32	0.87	3.57	0.48	2.89	0.49	8.98	8.61
Nd	12.60	7.00	4.40	6.30	11.60	11.60	3.50	57.6	125.1	10.76	32.5	5.29	1.01	4.18	0.54	2.85	0.46	31.9	18.29
Sm	2.25	1.02	0.78	1.24	1.98	1.76	0.56	16.3	32	2.87	9.2	1.05	0.17	0.67	0.09	0.51	0.1	6.40	4.39
Eu	0.27	0.14	0.18	0.24	0.42	0.32	0.11	14.8	37.9	2.88	8.5	1.37	0.17	1.23	0.17	1.08	0.21	0.74	3.93
Gd	2.28	0.77	0.74	1.00	1.68	1.35	0.80	33.7	100.3	8.89	37.6	6.04	1.13	5.22	0.65	3.41	0.57	6.20	11.80
Tb	0.41	0.16	0.14	0.14	0.28	0.18	0.13	36.5	62.3	7.48	28.6	4.33	0.81	3.51	0.44	2.12	0.39	1.10	8.28
Dy	2.18	0.89	0.67	0.87	1.57	0.94	0.71	34.8	72.1	5.02	15.2	2.33	0.48	1.97	0.26	1.23	0.26	6.70	8.23
Ho	0.63	0.19	0.19	0.18	0.36	0.15	0.14	6.2	16.9	2.06	8.2	1.75	0.46	1.58	0.27	1.51	0.34	1.50	2.37
Er	1.71	0.64	0.45	0.46	0.98	0.42	0.36	32.5	52.7	7.4	26.7	4.78	0.91	3.98	0.51	2.72	0.49	4.50	7.90
Tm	0.30	0.10	0.09	0.09	0.14	0.07	0.06	47.7	95.5	11.31	44.4	8.02	1.35	7.25	1.05	6.77	1.29	0.76	12.57
Yb	1.87	0.73	0.53	0.55	1.06	0.49	0.39	31.8	51.2	6.92	26.5	4.32	0.87	3.57	0.48	2.89	0.49	4.90	7.75
Lu	0.32	0.11	0.07	0.08	0.17	0.07	0.07	57.6	125.1	10.76	32.5	5.29	1.01	4.18	0.54	2.85	0.46	0.75	13.44
∑REE	102.53	54.99	33.45	53.05	69.63	66.84	23.33	481.5	970.5	101.98	367.5	61.69	11.5	52.14	7.04	40.32	33.45	13.79	141.40
∑LREE	92.56	51.26	30.39	49.44	62.97	62.85	20.56	185.9	356.5	39.26	139.3	23.49	4.31	19.65	2.67	15.74	30.39	33.18	67.80
∑HREE	9.70	2.59	2.88	3.37	6.24	3.67	2.66	280.9	576.1	59.84	219.7	36.86	7.02	31.26	4.20	23.50	2.88	13.79	71.50
∑LREE/∑HREE	9.54	19.79	10.55	14.67	10.09	17.12	7.73	0.66	0.62	0.65	0.63	0.64	0.61	0.63	0.64	0.67	10.55	10.05	6.44
La/Yb	9.89	17.95	15.85	24.73	14.25	29.80	13.33	1.02	1.03	1.07	1.01	1.11	1.05	1.11	1.06	0.94	1.00	53.87	10.56
La/Th	1.76	2.57	2.55	5.23	4.19	3.56	2.73	0.48	6.84	0.84	5.04	0.52	1.52	0.33	5.67	5.33	4.90	2.04	3.12
La/Co	13.21	21.83	4.94	9.07	25.17	11.23	3.71	18.06	32.94	6.73	20.54	3.98	0.65	2.84	0.51	2.72	0.06	40.4	12.14
(Eu/Eu*)	0.36	0.46	0.71	0.64	0.68	0.61	0.40	1.89	1.87	1.60	1.21	1.30	0.89	1.42	1.56	1.87	2.12	0.35	1.11

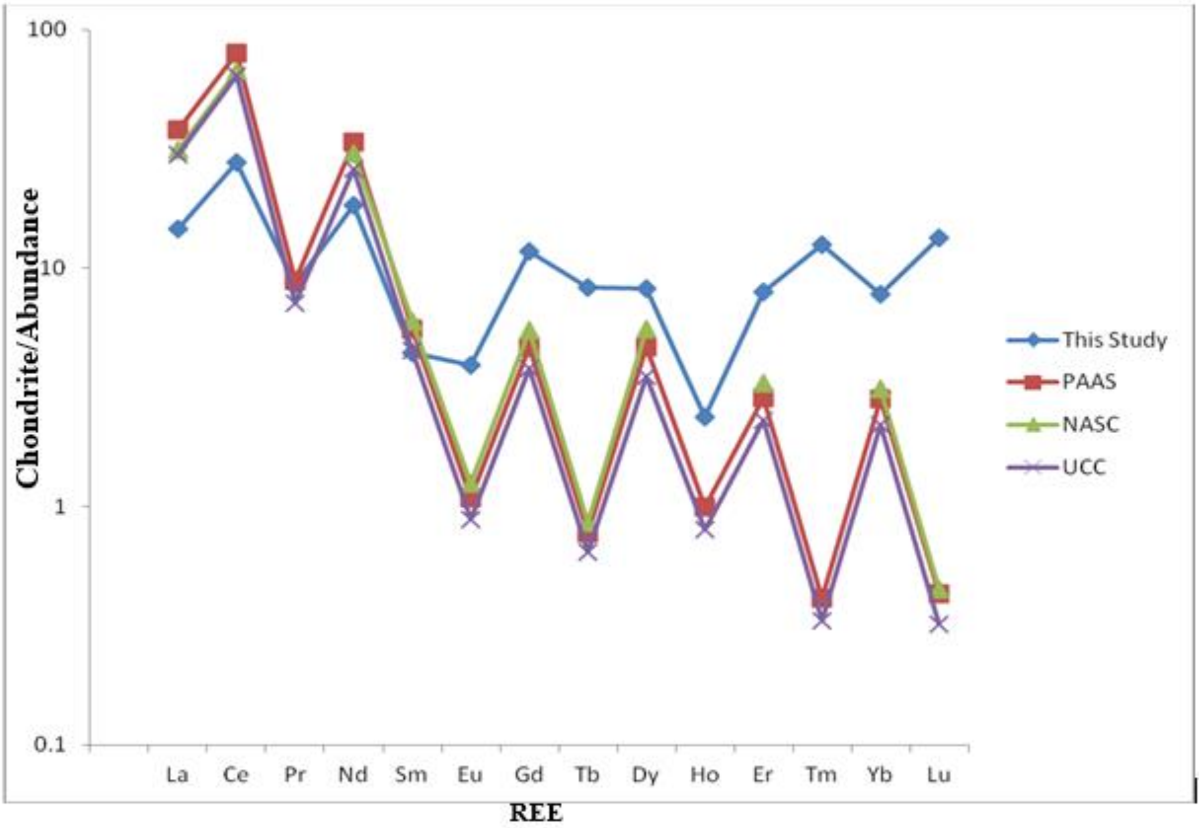


Fig. 3: Comparison of REE patterns between average Patti Formation sandstone, average Post-Archean shales (Taylor and McLennan, 1985), average North American Shale Composite (Gromet *et al*., 1984) and average of the Upper Continental Crust composition (Taylor and McLennan, 1985).

Tab. 6: Comparing average chemical composition of the Patti Formation Sediments with the average Crust sediment values

Elements/Ratios	This study	PAAS (Taylor & McLennan, 1985)	NASC (Gromet *et al.*, 1984)	UCC (Taylor & McLennan 1985)
SiO_2	86.00	62.4	64.80	66.00
Al_2O_3	6.11	18.78	16.90	15.20
Fe_2O_3	3.26	7.18	5.66	5.00
MgO	0.016	2.19	2.86	2.20
CaO	0.025	1.29	3.63	4.20
Na_2O	0.02	1.19	1.14	3.90
K_2O	0.12	3.68	3.97	3.40
P_2O_5	0.02	0.16	0.13	-
TiO_2	0.27	0.99	0.70	0.50
SiO_2/Al_2O_3	14.08	3.32	3.83	4.34
K_2O/Na_2O	6.00	3.09	3.48	0.87
Rb/Sr	0.23	0.80	0.88	0.32
Ba/Rb	15.88	4.06	2.90	4.91
Zr/Hf	38.87	42.00	31.75	32.76
Zr/Nb	50.40	11.05	15.38	7.60
Zr/Th	34.93	14.38	16.26	17.76

Tab. 7: Rare earth element (REE) concentrations of the Bida Sediments compared with the average Crust sediment values.

Rare Earth Elements	This Study	PAAS (Taylor & McLennan, 1985)	NASC (Gromet *et al.*, 1984)	UCC (Taylor & McLennan 1981)
La	14.53	38.2	31.1	30.0
Ce	27.82	79.6	67.03	64.0
Pr	8.61	8.83	NR	7.1
Nd	18.29	33.9	30.4	26.0
Sm	4.39	5.55	5.98	4.5
Eu	3.93	1.08	1.25	0.88
Gd	11.80	4.66	5.5	3.8
Tb	8.28	0.77	0.85	0.64
Dy	8.23	4.68	5.54	3.5
Ho	2.37	0.99	NR	0.8
Er	7.90	2.85	3.27	2.3
Tm	12.57	0.41	-	0.33
Yb	7.75	2.82	3.11	2.2
Lu	13.44	0.43	0.45	0.32
ΣREE	141.40	184.77	154.48	146.37
ΣLREE	67.80	66.08	134.51	131.60
ΣHREE	71.50	17.61	18.72	13.88
ΣLREE/ΣHREE	6.44	3.75	7.19	9.48
La/Yb	10.56	13.55	10.0	13.64
La/Th	3.12	2.62	2.53	10.71
La/Co	12.14	1.66	1.21	3.00
Th/Co	4.57	0.63	0.48	1.07
Th/U	4.41	4.71	4.62	3.82
(Eu/Eu*)	1.11	0.63	0.67	0.65

4.3 Sandstone Classification

The framework composition of the sandstones shows that using Folk (1974) classification, are mainly quartz arenites with few sub arkosic types (Fig. 4). The result is comparable to sandstones of the Maastrichtian Ajali and Enagi formations in Anambra and northern Bida Basins respectively (Tijani *et al.*, 2010; Ojo, 2012). Both the plots of log (Na_2O/K_2O) versus log (SiO_2/Al_2O_3) (Pettijohn *et al.*, 1972) and standard plot of Herron (1988) using log(Fe_2O_3/K_2O) versus log(SiO_2/Al_2O_3) were applied to interpret the present data. Most of the samples fall within the sub-litharenite, Fe-Sand, sub-arkose and quartz arenite regions (Fig. 5) which is also an indication of the enrichment of quartz in the samples.

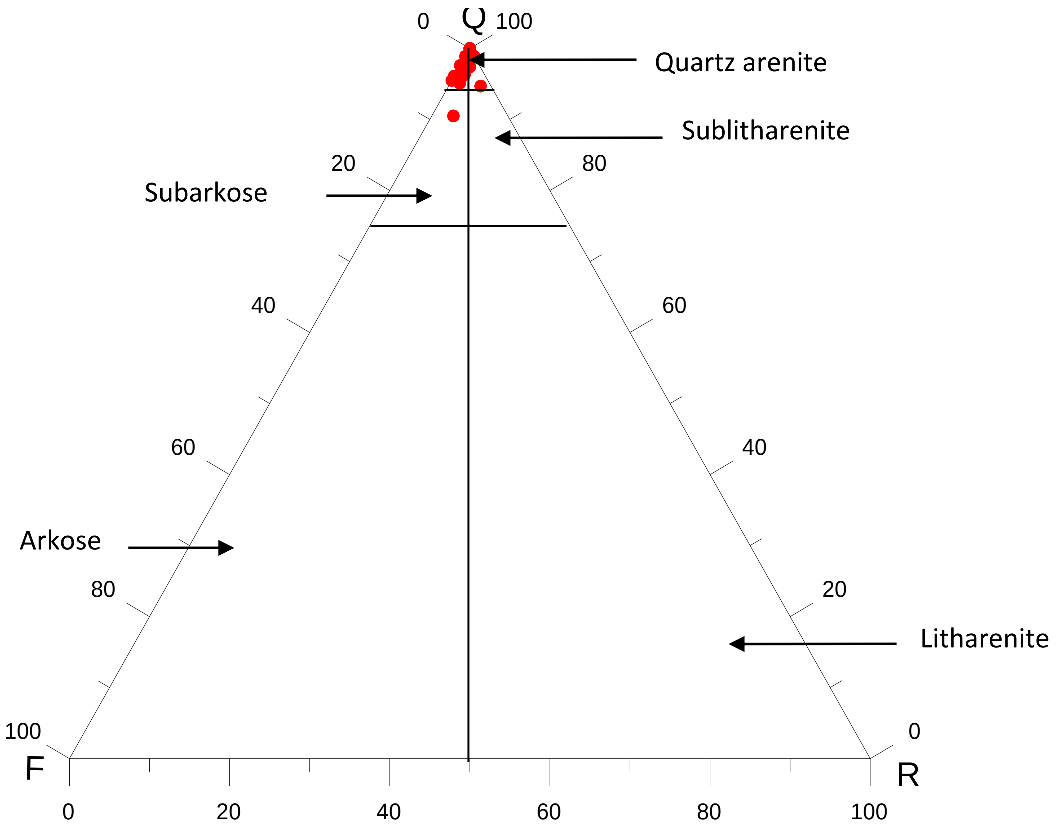
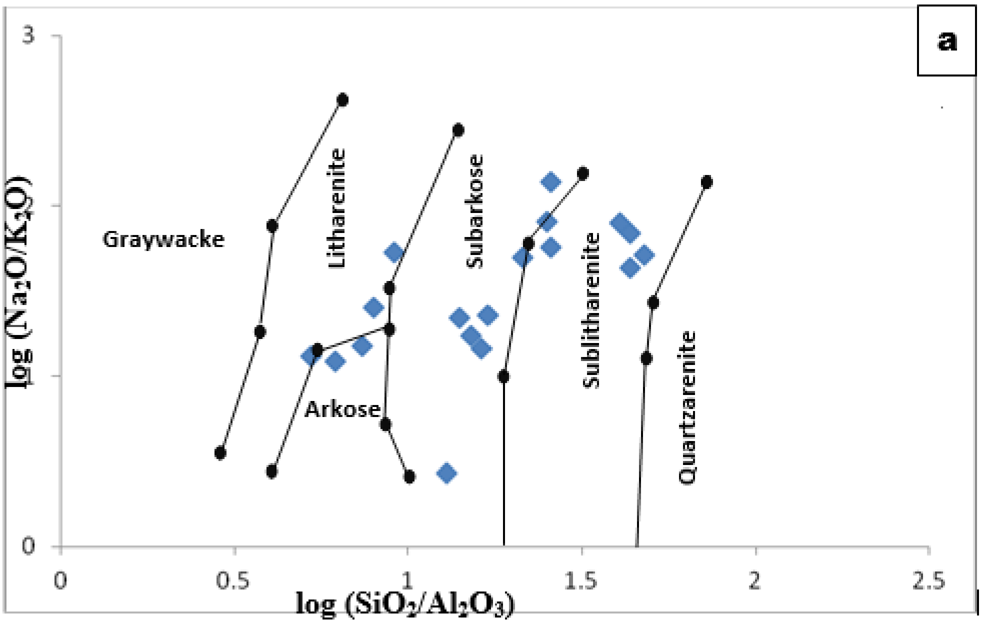


Fig. 4: Ternary diagram for the Patti Formation sandstones after Folk (1974) indicating that the sandstones are sub arkose and quartz arenite.



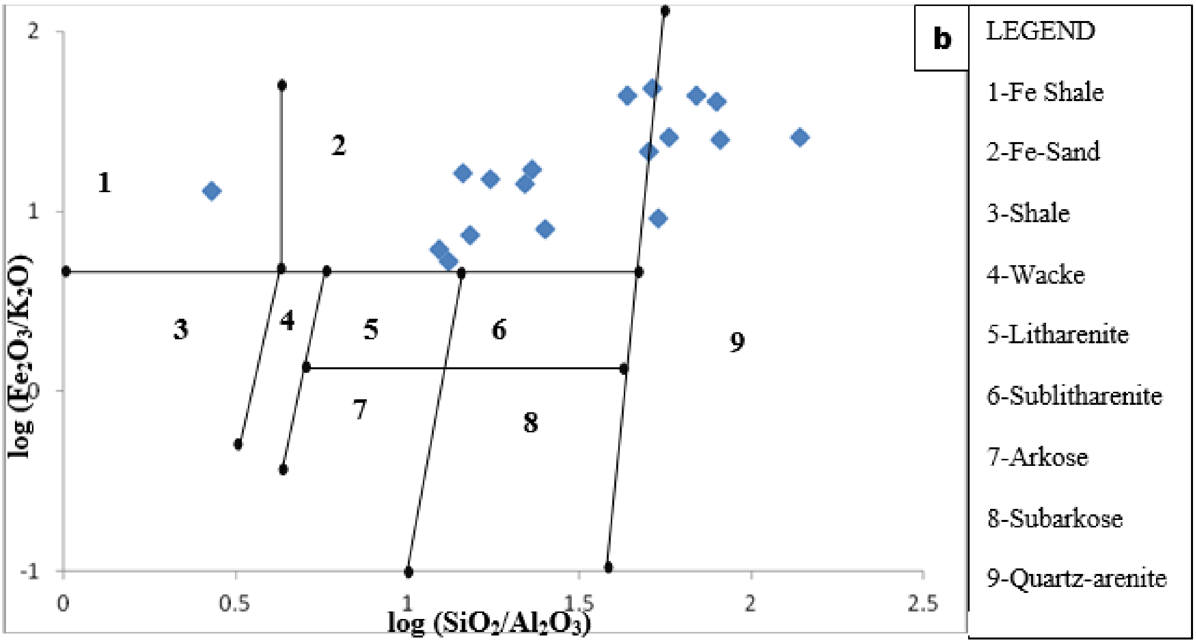


Fig 5: Chemical classification Scheme of Patti Formation sandstones based on (a) log (SiO_2/Al_2O_3) *vs.* log (Na_2O/K_2O) diagram of Pettijohn *et al.* (1972), and (b) the log(SiO_2/Al_2O_3) *vs.* log(Fe_2O_3/K_2O) diagram of Herron (1988).

4.4. Provenance

The provenance of the investigated sandstones are inferred using QFR diagrams, quartz types according to Dickinson and Suczek (1979) on one hand and major element, trace and rare earth elements geochemistry indicators (Garrels and Mackenzie, 1971; Bhatia, 1983; Feng and Kerrich, 1990). The QFR ternary plots for the investigated sandstones indicate continental block and metamorphic humid provenance (Dickinson 1988; Suttner *et al.*, 1981) (Fig. 6). Amajor (1990) deduced humid paleoclimatic and rifted continental basement settings for the provenance of sandstone facies of the Azu river group in the Benue trough based on the QFR diagrams. On this note, a regional correlation exists among equivalent Maastrichtian sandstones in the northern Bida Basin (Enagi Formation) and Anambra Basin (Ajali Formation) in Nigeria (Tijani *et al.*, 2010; Ojo, 2012).

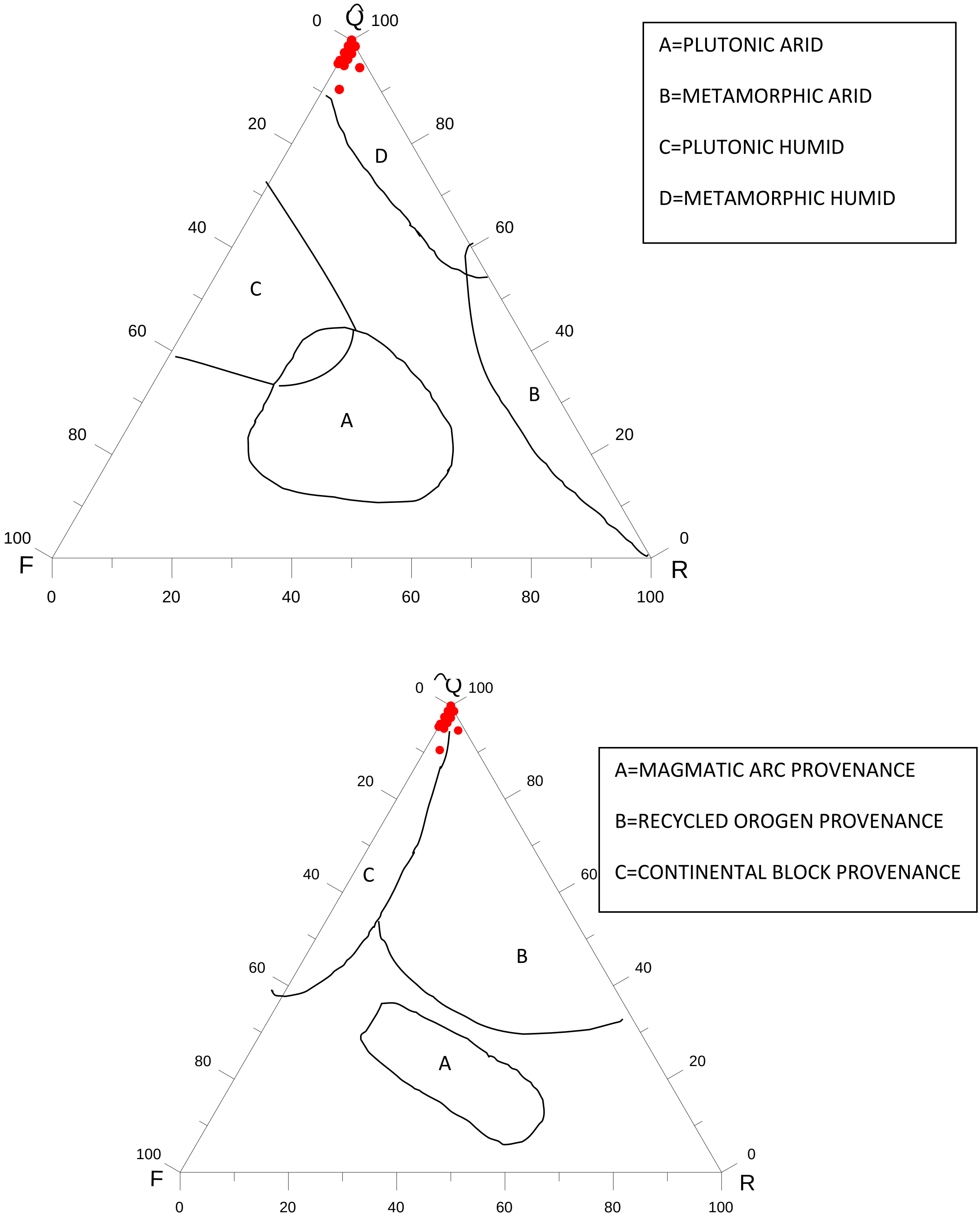


Fig. 6: QFR Ternary plots for provenance setting of Patti Formation sandstones (a) Modified after Dickson (1988) and (b) Modified after Suttner *et al*. (1981). Note Q = quartz, F = feldspar and RF = rock fragments

The compositional maturity and paleoclimatic setting of the sandstones are deducted from the bivariate plot of SiO_2 against total (Al_2O_3+K_2O+Na_2O) proposed by Suttner and Dutta (1986). This reveals increasing chemical maturity in predominantly warm semi-humid to humid conditions for the Patti Formation sandstones (Fig. 7).

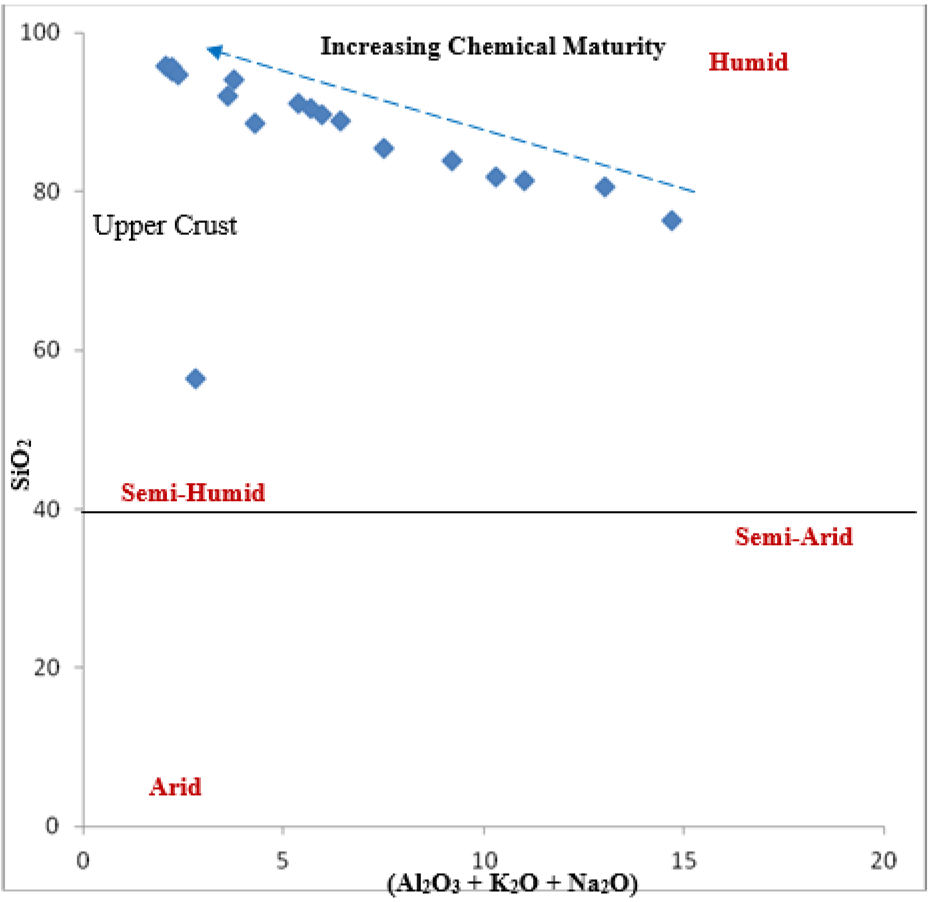


Fig. 7: A plot of SiO_2 versus (Al_2O_3+K_2O+Na_2O) showing the trend of maturity for Patti Formation Sandstone (after Suttner and Dutta, 1986).

According to Bhatia and Crook (1986) and Condie (1993), Th, Hf, Th and Zr abundances are usually higher in felsic igneous rocks and in their weathering products, whereas Co, Sc and Ni are more concentrated in mafic than in felsic igneous rocks The generally low concentrations of ferromagnesian trace elements such as Ni, Co and V in the sandstones indicate that they were principally derived from felsic source rocks. Mafic and igneous source rocks differ significantly in the ratios such as Th/Sc, La/Co, and Th/Co and hence provide useful information about the provenance of sedimentary rocks (Cullers *et al.*, 1988; Cullers, 1994, 2000; Cullers and Padkovyrov, 2000). Table 7 above shows the calculated value and the comparison with the standard for La/Co and Th/Co. The values are similar to sediments derived from felsic source rocks rather than mafic source rocks. Some Large Ion Lithophile Elements (LILE) and High Field strength Elements (HFSE) elemental ratios like Rb/Sr, Zr/Hf presented in table 4 can serve as indicators for paleotectonic setting reconstructions (Cullers *et al.*, 1979; Taylor and McLennan, 1985). Table 4 shows the mean value of High field strength elements (HFSE) Zr as 265.12 ppm which reflects granite rich source rock. The REE and Th are generally accepted as among the most reliable indicators of sediment provenance because their distribution is less affected by heavy-mineral fractionation than that of elements such as Zr, Hf, and Sn (Cullers *et al.*, 1979; Taylor and McLennan, 1985). High enrichment of LREE (average of 67.8 ppm) in the samples is controlled mainly by the abundance of heavy minerals like zircon which is corroborated by the presence of high amount of Zr element (see table 4). The average of Th/U ratio of the sandstones (4.50) is lower compare to that of PAAS (4.70), whereas La/Th average ratio (3.12) is higher than the PAAS (2.60) and NASC (2.53) but lower than UCC (10.71).

Three tectonic settings; Passive Margin (PM), Active Continental Margin (ACM) and Oceanic Island Arc (OIA) are recognized on the log (K_2O/Na_2O) versus SiO_2 discrimination diagram of Roser and Korsch (1986). The discrimination plot presented as Fig. 8 shows that Patti Formation sediments are sourced from mainly Passive Margin (PM). A similar but bivariate plot of TiO_2 versus (Fe_2O_3+MgO) also supported the passive margin tectonic setting (Fig. 9). Also, the application of petrographic data using QFR diagram after Suttner *et al.* (1981) also indicate a continental block provenance (see Fig. 6).

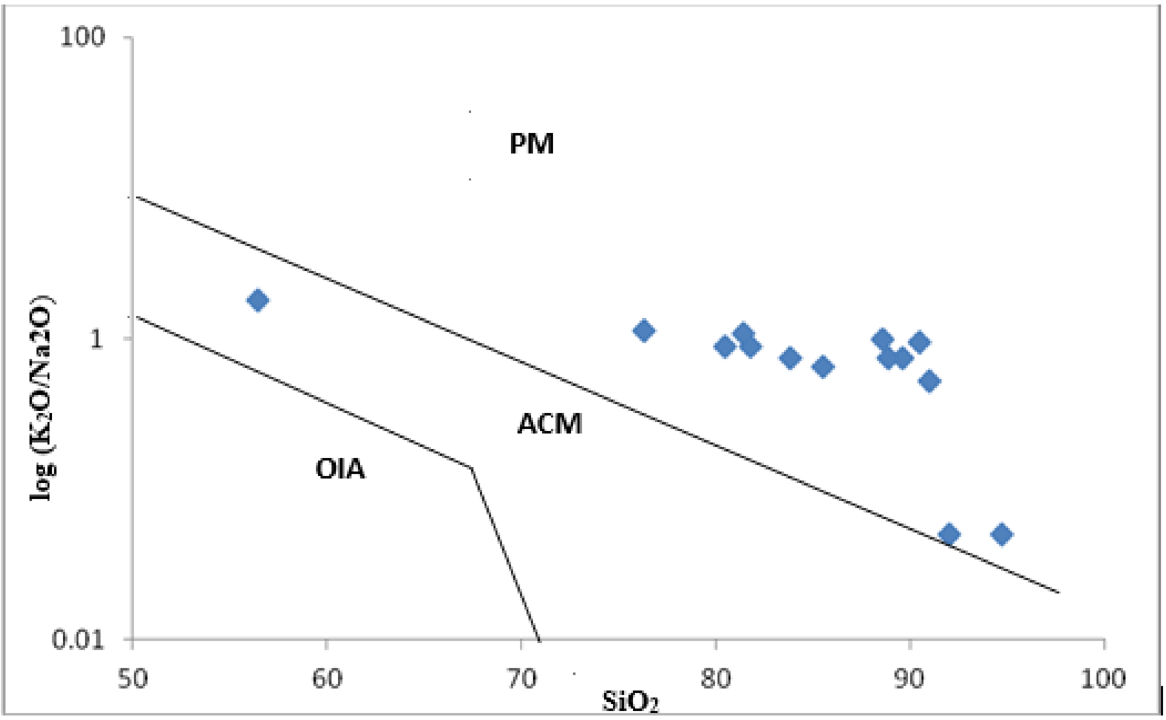


Fig. 8: Discrimination diagrams of Patti Formation sandstones (after Roser and Korsch, 1986). Note OIA - Oceanic Island Arc; ACM - Active Continental Margin; PM - Passive Margin.

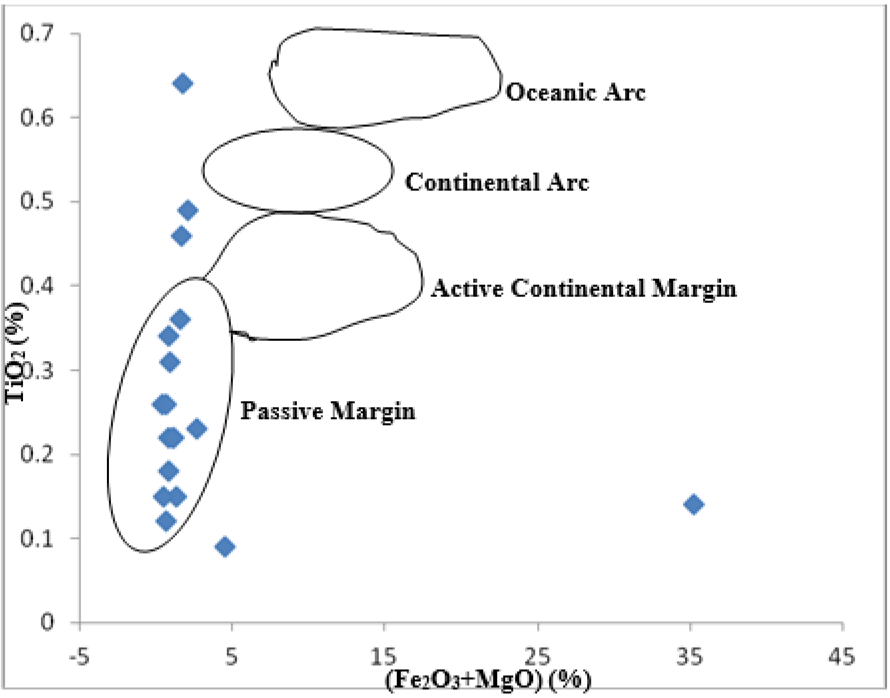


Fig. 9: The TiO_2 vs. (Fe_2O_3+MgO) bivariate plot discrimination diagram for the Patti Formation sandstones (after Bathia, 1983).

4.5. Weathering History and Compositional Maturity

Alteration of igneous rocks during weathering results in depletion of alkali and alkaline earth elements and preferential enrichment of Al_2O_3 in sediments. Therefore, 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). Chemical composition is largely dependent on the composition and weathering conditions at the source rock area (Nesbitt and Young, 1989; Nesbitt *et al.*, 1996). A measure of the degree of chemical weathering/alteration of sediment's source rock can be constrained by calculating the chemical index of alteration (CIA) and Plagioclase index of alteration (PIA) (Fedo *et al.*, 1995). The signatures of alteration of plagioclase and potassium feldspars to clay minerals can be obtained from CIA data. In this study, the average Chemical Index of Alteration (CIA) values for the sandstones of Patti Formation is 96.49 on the average, while PIA is 99.05 (see Table 2). Nesbitt and Young (1982) suggested that high values (between 76 and 100) indicate intensive chemical weathering in the source areas whereas values less than or equal to 50 indicates fresh source areas. Also, high CIA and PIA values (between 75 and 100) indicate intensive weathering in the source area whereas low values (≤ 60) indicate low weathering in the source area (Osae *et al.*, 2006).

Generally, the sandstones of Patti Formation are characterized by comparatively higher SiO_2 content (average of 86.8 %) and lower Al_2O_3 (6.11 %) content (see Table 2). The sandstones also show a comparative lower content of Na_2O (0.01-13.30 %) and K_2O (0.01-0.27 %). The values suggest that sandstones of Patti Formation are mineralogically matured. The SiO_2/Al_2O_3 ratio can be employed as an index of sediment maturity as the values would increase because of increase in quartz content at the expense of less resistant components such as feldspar and lithic fragments during sediment transport and recycling (Potter, 1978). The SiO_2/Al_2O_3 ratio is about 3 in basic rocks (basalts and Gabbros) and it is around 5 in the acidic end member (granites and rhyolites) while ratio of more than 5 or 6 in sedimentary rocks provided evidence of sedimentary maturation (Roser *et al*., 1996). The average ratio of SiO_2/Al_2O_3 is 21.38, thereby supporting the mineralogical maturity of the Patti sandstones. Average for the Agbaja and Ihe samples is very high about 37.4 indicating that sediments in the area are more mature and this positively correlate with Rb/Sr trend in the area. Increase in the value of SiO_2 and corresponding decrease in the value of Al_2O_3 and Fe_2O_3 as shown in Table 2 and 3 are an indication of weathering and maturity of the sands. It is also noted that average SiO_2 value is greater than the average weight of UCC, NASC and PAAS (Table 7).

The ratio of Na_2O/K_2O can be used to determine both the provenance and diagenesis of the sandstone deposit, as alkali abundance characterizes immature sandstones whereas low concentration show mature sandstone (Roser and Korsch, 1986). The alkali content (Na_2O+K_2O) is also a good indicator as it measures the feldspar content (Rollinson, 1993). Na_2O/K_2O and Na_2O+K_2O values range from 0.02 to 5.56 % (average 0.67) and 0.02 to 0.94 % (average 0.14 %) for Na_2O/K_2O respectively. The low values of the alkali contents thus lend support to the compositional maturity of the Patti Formation. The relatively high mean value of K_2O/Na_2O (8.39) is attributed to the presence of albitic plagioclase, K-feldspar, mica and illite (Pettijohn, 1963, McLennan *et al.*, 1983, Nath *et al.*, 2000). TiO_2/Al_2O_3 which is an indication of chemical maturity is low in the study area ranging from 0.02 - 0.15 % (average - 0.06) indicating that the sediments are chemically matured (Bakkiaraj *et al*., 2010). The ratio of K_2O/Al_2O_3 ranges from 0.002 - 0.280 (average - 0.029) and suggests source area weathering. Bauluz *et al.* (2000) reported that K_2O/Al_2O_3 ratio is an indication of sedimentary recycling. Depletion of Na_2O (<1 wt %) in the sandstones can be attributed to the relatively small amount of Na-rich plagioclase present while K_2O and Na_2O contents and their ratios (K_2O/Na_2O>1) are also consistent with observed K-feldspar more than plagioclase feldspar in the thin sections (see Table 1). The high amount of Sr and Ba in samples from Ozi and Abaji may however be attributed to good showing of plagioclase feldspar (Feng and Kerrich, 1990).

The Th/U ratios in weathering products are usually higher than UCC values of 3.5 to 4.0 (McLennan *et al.*, 1993). The Th/U ratio of the analyzed samples ranges from 2.06 to 9.08 (mean of 4.5, table 4) indicating moderate chemical weathering within the study area and recycling of sediments from the crust. The average La/Th ratios (averaging 3.12) is higher than UCC (2.80), NASC (2.55) and PAAS (2.60) (see Table 6) and this suggests coherent behavior between REE (La) and Th and stronger grain size effect on sediments than that of provenance (Fig. 10). The Rb/Sr ratios of sediments also monitor the degree of the source-rock weathering (McLennan *et al*., 1993). The average ratio of Rb/Sr for the Patti sandstones (0.29) is lower than the average of Upper Continental Crust (0.32) and average Post-Archean Australian Shale (0.80), therefore indicating significant weathering in the source area. Little variation in the Rb/Sr values in the locations studied, with the values in Agbaja and Ihe samples lower than the average of all the samples. It is possible that present day weathering in the locations could be one of the factors.

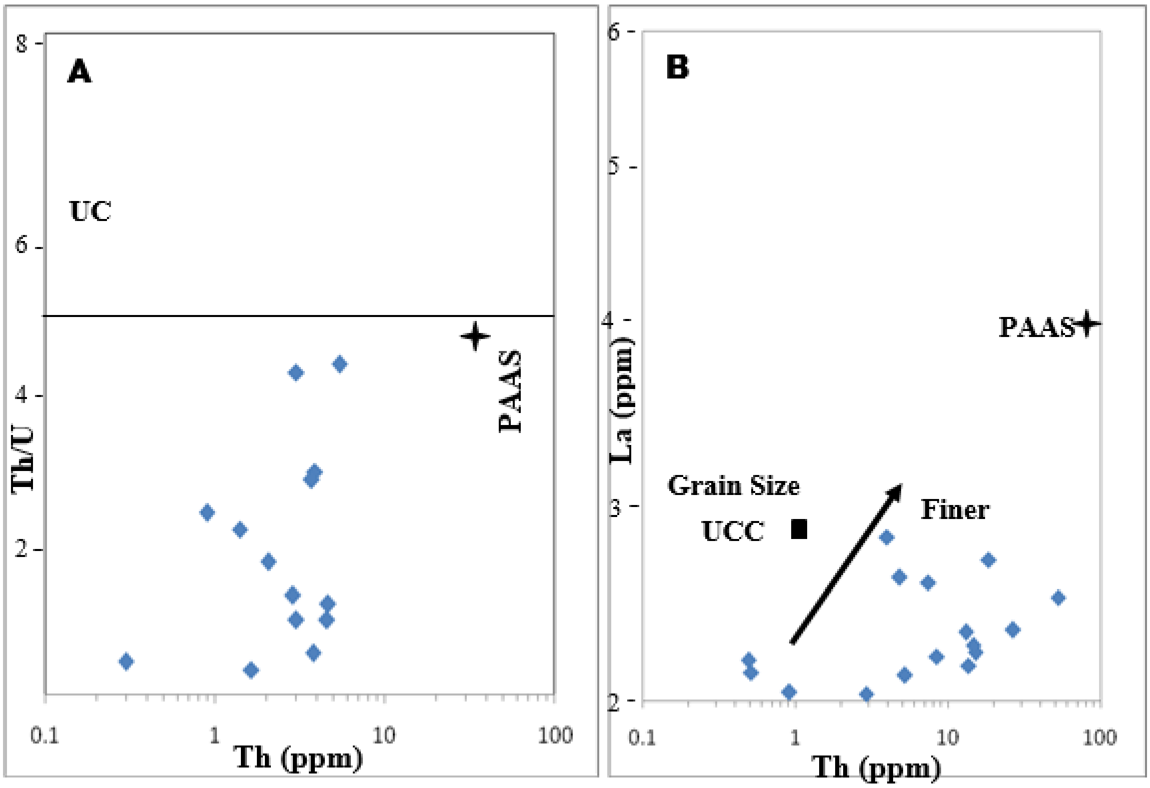


Fig. 10: Plots of; (A) Th vs. Th/U and (B) Th vs. La for evaluating sedimentary Patti Formation sandstone sorting and provenance (after McLennan *et al.*, 1993). Note the comparison values of UCC and PAAS as shown in the plots.

Other useful indicator of composition maturity are Zr/TiO_2 and La/V. Zhang (2004) explained that certain mafic minerals are prone like pyroxene, olivine and opaque oxides that are relatively enriched in Ti and V are prone to degradation and therefore unstable during sedimentary proceses. However, other minerals like zircon, apatite, tourmaline, monazite usually enriched with in Zr and La are more resistant and survive transportation and recycling. The ratios thus increase as maturity increases. Average Zr/TiO_2 and La/V values (0.1 and 0.66 respectively) in the analysed samples are high and the ratio increases as compositional maturity increases.

5. Conclusion

Petrographic and geochemical data of the Patti Formation sandstones show they are to arenites-types (dominantly quartz arenites and lithic arenites) with minor subarkosic type. The little feldspar present is dominated by K-feldspar and the matrix is dominated by kaolinitic clay mineral.

Compositional maturity of the sandstones is high and was probably influenced by warm humid paleoclimatic setting and sediments recycling. They show enrichment of SiO_2 due to the weathering of the less resistant elements such as K_2O and Na_2O leaving a greater concentration of the more resistant silica. The various maturity indicators reveal relatively higher maturity of sandstones at Agbaja and Ihe than those sampled from Ozi, Gerinya and Abaji areas.

The sediments were derived mainly from quartz rich, felsic igneous rocks and probably from an older sedimentary source. A passive margin and uplifted continental provenance is inferred for the sandstones. This is significant as it provides further evidence of the geological setting of the Bida Basin widely believed to be intracratonic.

The sediments were most probably recycled partly from older Lokoja Formation (originally sourced from Precambrian basement rocks of the southwest Nigeria). Great similarities exist in the composition of the studied sandstones and that of Maastrichtian Ajali Formation in the adjacent southern Anambra basin. The tethys sea from the north could have played significant role in reworking of the sands and consequently their compositional maturity.

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