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Geochemical Provenance, Source Area Weathering, and Tectonic Setting of the Bida Sandstone in the Northern Bida Basin, Northcentral Nigeria

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Abstract - This paper aims to determine the geochemical provenance, source area weathering, and tectonic setting of the Bida sandstone exposed at Doko and Jima in the Northern Bida Basin, Northcentral Nigeria. Geological fieldwork was carried out and sandstone samples were collected and analyzed for major element concentrations using X-Ray Fluorescence (XRF) method. Major element abundance shows that the studied sandstone samples consist of SiO_2 (average 71.42%), Al_2O_3 (average 15.16%), and CaO (average 0.26%) constituting about 90% of the bulk rock composition. While P_2O_5, Na_2O, K_2O, MgO, TiO_2, MnO, and Fe_2O_3 constitute about 10% of the composition. The results obtained using the Al_2O_3/TiO_2 ratios show that the sandstones derived from intermediate to felsic igneous rocks. The A-CN-K triangular diagram shows that majority of the analyzed samples plotted on the aluminum zone towards kaolinite shows predominantly intermediate degree of weathering except for one sample which falls towards the CN-K line, indicating the different degree of weathering (perhaps an existence of differential weathering in the area). The source area weathering indices which include CIA (68.6%), CIW (71.20%), and PIA (54.66%) further confirms that the sediments have been subjected to intermediate weathering. The K_2O/Na_2O versus SiO_2 tectonic setting discriminant plot shows that the samples are dominantly deposited in the passive margin setting. It is, therefore, concluded that the Bida sandstone analyzed was sourced from predominantly felsic igneous rocks where the degree of chemical weathering was intermediate and in the passive margin setting.

Keywords: Doko Member, Jima Member, Nupe Basin, geochemistry, sandstone, passive margin

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Introduction

Background

Sedimentary rocks are important source of information about previous orogenic conditions and the composition of which may describe the evolution of provenance and tectonic setting (Peterson, 2009). Sedimentary rocks are the only evidence of an ancient upper crust and may have been removed by erosion, covered with sediment and ice, or buried deep within the crust. The combination of detritic and geochemical compositions of sedimentary rocks provides important information about their origin and tectonic setting characteristics (Etemad-Saeed *et al*., 2011). Many factors influence sediment composition, namely source rock composition, chemical weathering, climate, transport burial, and diagenesis. As the sediment composition changes through time, the geochemical characteristics of the sediment can be used to understand its geologic history. Thus, the geochemical characteristics of clastic sedimentary rocks are useful in determining the depositional setting and its associated provenance.

The Bida Basin, which is also known as the Mid-Niger or Nupe Basin, is located in north-central Nigeria. The Bida Basin trends NW−SE extending from Kontagora in the north to the area slightly beyond Lokoja in the south (Obaje *et al*., 2020). It is bounded in the NE and SW by the basement complex, and merges with the Anambra and Sokoto Basins to the SE and NW respectively (Obaje *et al*, 2011). After the deposition of sediments in a sedimentary basin, the sedimentary rocks usually retain information about the past orogenic conditions under which the rocks in the basin were formed. Therefore, information on the previous orogenic condition of the Bida sandstone can be inferred from analyzing rock samples from the basin. The study of major and trace element geochemistry helps in giving information on source provenance, tectonic setting, and source area weathering, which can be deduced from the geochemical signatures of the clastic rocks. These pieces of information can be determined using various bivariate plots and triangular diagrams established by various workers (*e.g*. Nesbitt and Young, 1982; Bathia, 1983; Roser and Korsch, 1986).

Previous works on the evaluation of the source area weathering and tectonic setting of the Bida sandstone in northern Bida Basin are limited in literature. Recent work, especially that of Adepoju *et al*. (2021) focused on determining the petrofacies, its provenance, and tectonic settings. This study, therefore, employs major element geochemistry to determine the source provenance, tectonic setting, and source area weathering of part of the Bida sandstone in the northern Bida Basin, Northcentral Nigeria. The work will assist as a baseline study, and will provide background information for the geochemical studies (source area weathering and tectonic setting) of the Bida Basin using major element geochemistry for future exploration studies.

The studied area is situated in Doko and Jima Villages near Bida Town in the northern Bida Basin. The locations of the studied exposures are as shown in Figure 1. The relief of the area is generally upland with the heights up to 900 ft. (about 274 m) above sea level, and the major drainage is the

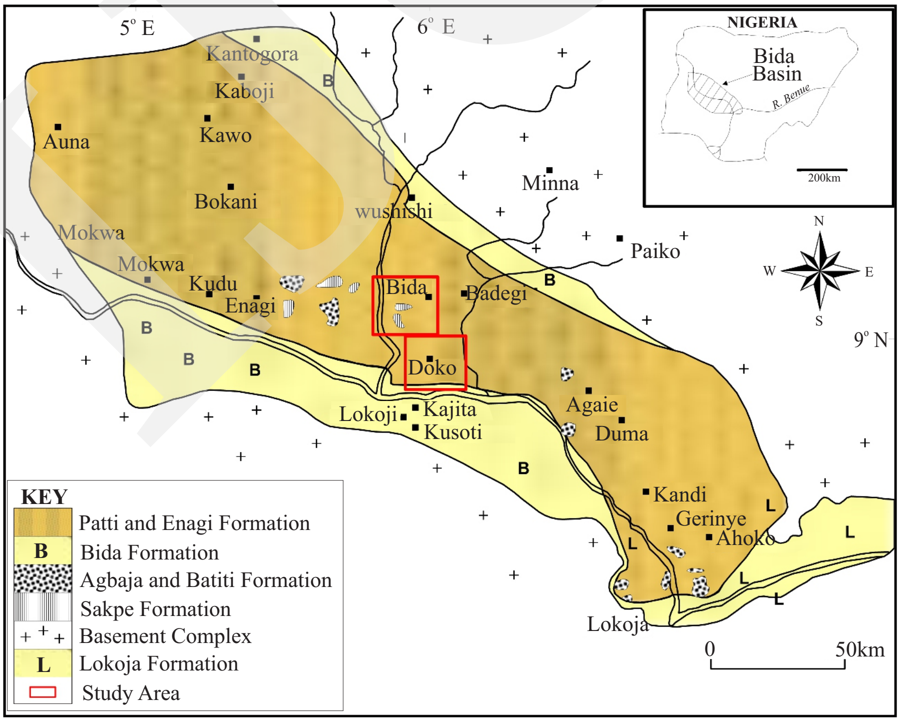

Figure 1. Geological map of Bida Basin showing the studied exposure locations (modified from Obaje *et al*., 2011).

River Niger and other major distributaries are Kaduna, Gurara, and Gbako Rivers (Falconer, 1911).

Geological/Stratigraphical Setting of Bida Basin

The upper Cretaceous Bida Basin of Central Nigeria is sandwiched between the Precambrian schist belts of the northern Nigerian massif and the West African Craton. Adeleye (1974) carried out a detailed geological mapping in the basin, and micropaleontological studies was carried out by Jan du Chene and Salami (1978), who documented the palynomorph-foraminiferal associations and interpreted paleodepositional environments of the Lokoja and Patti Formations as generally being a shallow marine. Akande *et al*. (2005) interpreted sedimentary succession in the southern Bida Basin. The southern Bida Basin has received more research contributions to advance our understanding, especially in the areas of geology, sedimentary history, and paleogeography (Adepoju *et al.*, 2020).

The tectonic features of the Bida Basin have been the subject of debate for many years, and to date no satisfactory explanation for the origin of the basin has yet been accepted by geoscientists (Rahaman *et al.*, 2019). The stratigraphic succession of Bida Basin is classified into four major lithologic units based on the litho-stratigraphic variations. These lithologic units are Batati Ironstone Formation, Enagi Siltstone Formation, Sakpe Ironstone Formation, and Bida sandstone. The Batati ironstone is the uppermost unit in the sedimentary sequence of the Bida Basin. It is composed of oolitic and goethitic ironstone and kaolinite oolites, and it is divided into two members namely Kutigi and Edozhigi Members. Enagi Siltstone Formation is composed of siltstone and subordinate sandstone, siltstone, and sandstone mixtures. It correlates with the Patti Formation in the Lokoja Subbasin. Rootlets and fossil leaf impressions have been observed within the formation. The formation ranges in thickness from 30 to 60 m. The Sakpe Ironstone Formation is composed of dark brown coarse oolithic and pisolithic ironstones. Oolithes mainly occur in upper and lower parts, while pisolites occur mainly at the middle yelowish brown clay matrix. This formation is divided into two members: Baro and Wuya. The Baro Member consists of terrigenous sandstone, locally pyretic and concretionary, while The Wuya Member comprises oolitic and pisolitc ironstone with locally developed clay stones.

The Bida Formation is subdivided into Doko and Jima Members. The Doko Member is the basal unit, and composed mainly of very poorly sorted pebbly arkoses, subarkoses, and quartzose sandstones. The Jima Member is majorly made up of cross-stratified quartzose sandstones, siltstones, and claystones (Ajama *et al.*, 2017). The Jima Member overlies the Doko Member, of the quartzose sandstone, brownish, massive beds cross-stratified with subsidiary subgrey wackes, siltstones, claystones, and breccias. There are presence of trace fossils comprising *Ophiomorpha* burrows. Such burrows were also observed in the overlying Sakpe ironstone. This suggests a shallow marine subtidal to intertidal influence during sedimentation. The Jima Member is, therefore, seen as the more distal equivalent of the upper part of the Lokoja sandstone due to similar features. Lokoja, Patti, and Agbaja Formations are the rock units found in the southern part of the basin as seen in Figure 2.

The Bida sandstone is probably of the Campanian-Maastrichtian age, a flat-lying formation. It is the most dominant and basal lithology of the Bida Basin of the Middle Niger Valley. It comprises mainly sandstones and subsidiary breccias, siltstones, and claystones which are cyclically arranged along vertical profiles (Adeleye, 1973).

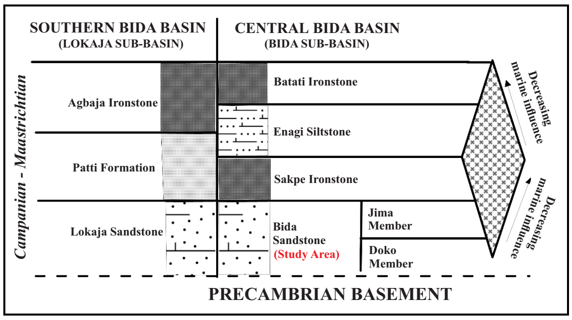

Figure 2. Stratigraphic succession in the Bida Basin (modified from Obaje *et al.*, 2011).

Sandstones are composed of five major ingredients: rock fragments (lithic grains), feldspar grains, quartz grains, matrix, and cement. The matrix consists of clay minerals and silt-grade quartz, and in most cases, the fine-grained material is deposited along with the sand grains. It can form from the diagenetic breakdown of labile (unstable) grains; however, clay minerals can be precipitated in pores during diagenesis. Cement is precipitated around and between grains, also during diagenesis; common cementing agents are quartz and calcite. Diagenesis stains the sandstone red. The composition of sandstone is largely a reflection of the geology and climate of the source area. Some grains and minerals are mechanically and chemically more stable than the others.

Methods and Materials

Geological fieldwork was carried out in Doko and Jima areas where different sections of the exposure of Bida sandstone were studied. The traditional traversing method and the Global Positioning System (GPS) were used for locating the outcrops. The different beds of each of the sections were described and logged using attributes of the beds, such as colour, texture, bed thickness, bed contact, and sedimentary structures. The materials used for this project work are rock samples from the Jima and Doko areas collected during the fieldwork. A total number of five samples were taken to the Nigerian Geological Survey Agency (NGSA) Kaduna for the laboratory analysis. X-Ray Fluorescence (XRF) was conducted to determine the major oxides and trace elements present in each sample. However, it is only the major elements that are reported in this work.

The target pulverizing machine (planetary micro mill pulverisette7) was used to pulverize (grind to fine powder) the samples. The grounded samples were ensured to pass 150 μ mesh sieves. This was done in order to ensure homogeneity of the samples. As much as 5.0 g of the pulverized sample was weighed and poured into a beaker; 1 g of binding aid (starch soluble) was added. The mixture was thoroughly mixed together to ensure homogeneity, and was pressed under high pressure (6 "tone") in order to produce pellets. It was labeled and packaged ready for the analysis where Energy Dispersive X-Ray Fluorescence (EDXRF) spectrometer of model "Minipal 4" was used. The pellets were carefully placed in the respective measuring positions on a sample changer of the machine, and the respective samples were measured by clicking the respective positions of the sample changer. LOI was determined gravimetrically by heating 1.0 g of the powdered sample in a cleaned weighed crucible at 1000°C. The crucible and the content were weighed to get the difference in weight before and after heating.

$$LOI = (a\text{-}b/1) \times 100\% = H_2O^+$$

Where

a = weight of crucible + 1g of the sample before heating

b = weight of crucible + 1g of the sample after heating.

Results and Discussion

The X- Ray Fluorescence (XRF) results of the major elements which are in their respective oxide forms (SiO_2, Al_2O_3O, SO_3, P_2O_5, Na_2O, K_2O, MgO, CaO, TiO_2, MnO, Fe_2O_3) for the representative Bida sandstone samples are summarized in Table 1. The ranges of each of concentration of the major elements are shown below in wt%:

SiO_2 (61.00–91.90), Al_2O_3 (0.21−22.20), SO_3 (0.04− 0.50), P_2O_5 (none detected), Na_2O (0.02 −0.04), K_2O (0.01−0.56), MgO (0.009−0.02), CaO (0.29−1.00), TiO_2 (0.03−3.64), MnO (0.02−0.055), Fe_2O_3 (2.58–14.49), and H_2O^+ (1.60–7.57). Tables 2 and 3 give a summary of the average major element oxides (wt%) data for the samples under study in comparison with that of the average sandstone from other sedimentary basins in Nigeria (Niger Delta Basin), and also the average sandstone worldwide.

In order to assess the degree of chemical weathering in the source area, the Chemical In-

Table 1. Results of Major Element Concentration in the Sandstones in Doko And Jima Areas of Bida Basin

Sample Code	SiO_2	Al_2O_3	SO_3	P_2O_5	Na_2O	K_2O	MgO	CaO	TiO_2	MnO	FeO	Fe_2O_3	H_2O^+
JM1A	91.9	0.21	0.50	Nd	0.02	0.46	0.020	1.00	0.57	0.02	2.32	2.58	1.60
JM1B	76.00	17.00	Nd	Nd	0.03	0.24	0.009	0.29	0.35	0.055	2.70	3.00	2.00
DKU1	64.00	16.00	Nd	Nd	nd	0.56	nd	0.34	0.03	0.02	13.04	14.49	4.01
DKL2	61.00	20.40	0.04	Nd	0.04	0.40	nd	0.30	2.06	0.038	8.04	8.94	6.74
JM2	64.21	22.20	Nd	Nd	nd	0.01	0.020	0.35	3.64	0.03	7.15	7.95	7.57
Average	**71.42**	**15.16**	**0.05**	**-**	**0.03**	**0.33**	**0.02**	**0.26**	**1.33**	**0.032**	**8.87**	**4.38**	**166.16**

Table 2. Comparison of the Average Concentration of Major Elements (in wt%) from Studied Area with Average Sandstones from Nigerian Basins

Oxides (wt%)	Present study	Niger delta Basin (Ikhane *et al*., 2014)	Sokoto Basin (Bassey and Eminue, 2014)
SiO_2	71.42	81.39	84.1
Al_2O_3	15.16	10.16	5.07
SO_3	0.04	-	-
P_2O_5	-	0.03	-
Na_2O	0.03	0.01	0.08
K_2O	0.33	0.04	0.07
MgO	0.016	0.04	0.02
CaO	0.27	0.02	0.12
TiO_2	1.33	1.16	-
MnO	0.032	0.02	-
Fe_2O_3	8.87	2.41	6.13
H_2O^+	4.38	-	-

Table 3. Comparison of the Average Concentration of Major Elements (in wt%) from Studied Area with Average Sandstones Worldwide

Oxides (wt%)	Present study	Passive margin (Bhatia, 1983)	Arkose (Pettijohn, 1963)
SiO_2	71.42	81.84	90.95
Al_2O_3	15.16	8.41	1.81
SO_3	0.05	-	-
P_2O_5	-	0.10	0.12
Na_2O	0.03	1.56	1.07
K_2O	0.33	2.91	1.71
MgO	0.016	0.52	1.39
CaO	0.26	2.81	1.89
TiO_2	1.33	0.31	0.49
MnO	0.03		0.05
Fe_2O_3	8.87	2.37	3.28
H_2O^+	4.38	-	-

dex of Alteration (CIA) proposed by Nesbitt and Young (1982) as well as those for Chemical Index of Weathering and Plagioclase Index of Alteration (PIA) were computed, and these parameters as well as the Al_2O_3/TiO_2 ratios for describing source provenance are summarized in Table 4,

Table 4. Summary of the Data for Ternary Diagram and Indices for Source Area Weathering and Provenance Determinations

Sample	Source Area Weathering Ternary Diagram end Members			Source Area Weathering Indices			Provenance Indicator Ratio
	Al_2O_3 (A)	K_2O(K)	$CaO+Na_2O$(CN)	CIA	CIW	PIA	Al_2O_3/TiO_2
JM1A	0.12	0.27	0.60	12.42	17.07	-32.47	0.4
JM1B	0.97	0.01	0.02	96.81	98.15	98.13	48.6
DKU1	-	-	-	-	-	-	533.3
DKL2	0.96	0.02	0.02	96.50	98.36	98.32	9.9
JM2	-	-	-	-	-	-	6.1
Average				**68.6**	**71.20**	**54.66**	**119.66**

and the A–CN–K ternary diagram for source area weathering is shown in Figure 3.

In other to determine the tectonic setting of the sandstone samples under investigation, Roser and Korsch diagram using K_2O/Na_2O versus SiO_2 to discriminate tectonic settings of terrigenous sedimentary rocks was produced in Figure 4. The discrimination diagram recognizes three fields which are oceanic-island-arc setting, active continental margin setting, and lastly passive margin setting. The fields where the data points for the samples examined fall in determines the tectonic setting where the samples originated from.

The major element abundance shows that the sandstone consists of SiO_2 (71.42%), Al_2O_3 (15.16%), and Fe_2O_3 (8.87%). It constitutes more than 90% of the bulk chemical composition, suggesting that the sandstones contain a significant amount of iron which could be attributed to ferruginous cement.

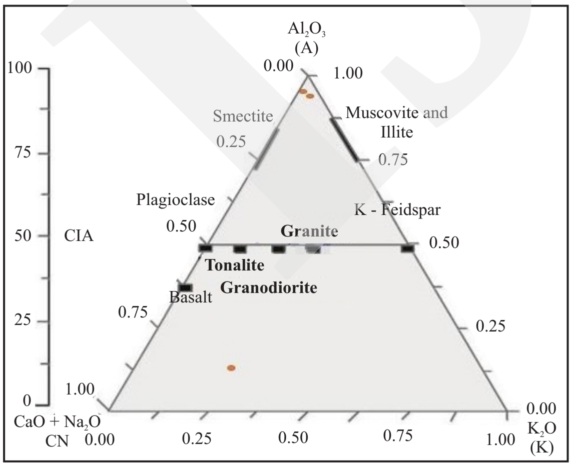

Figure 3. A–CN–K ternary diagram of molecular proportions of the sandstone samples of northern Bida Basin showing weathering trend of the sediment (after Nesbitt and Young, 1984).

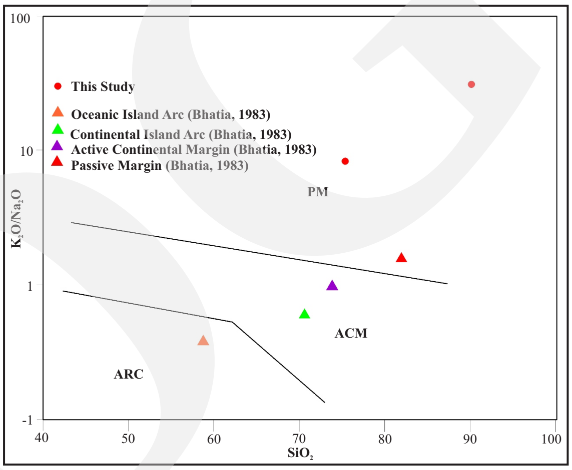

Figure 4. SiO_2 versus K_2O/Na_2O plot of Roser and Korsch (1986). Fields for oceanic island arc (ARC), continental margin arc (ACM), and passive margins (PM) are shown.

The comparison of the abundance of some selected major elements (wt%) in the studied sandstones with those of Nigerian Basins shows that the average concentrations of SiO_2 is lower, while those Al_2O_3 and Fe_2O_3 are higher than the average sandstones from other Nigerian Basins. The contents of the K_2O, Na_2O, and TiO_2 are also higher than that of the average sandstone of other Nigerian Basins (Ikhane *et al.*, 2014). The comparison of abundance of selected major elements in (wt%) in the studied sandstones with the average worldwide sandstones shows that the concentrations of SiO_2 is also lower, but the

Al_2O_3, Fe_2O_3, and TiO_2 are higher than the average worldwide sandstones (Bhatia, 1983).

Higher K_2O/Na_2O ratio (8 to 23) indicates the dominance of feldspar, illite, and mica. Bearing in mind that Al_2O_3 resides in feldspars, while TiO_2 in mafic minerals, the Al_2O_3/TiO_2 ratio of 0.4 – 533.3(averaged 119.66) reveals that these rocks come from a predominantly felsic source with minor contribution from intermediate igneous rocks. This is also supported by the depletion of MgO in the samples.

The weathering effect of the studied samples was evaluated using the molar percentage of major oxide components. The Chemical Index Alteration results obtained for the studied samples range between 12.42−96.81% (averaged 68.58%), the CIW with a range of 17.07 −98.36% (averaged 71.20%), which indicates predominantly intermediate weathering of the source materials. An average of 54.66% with a range of -32.47−98.33% was acquired for the PIA values indicating unaltered to intermediate degree of alteration. However, the analytical result for sample 1 (PIA = -32.47%) is suspected to be erroneous and may not be reliable. The above interpretation of intermediate weathering of the source materials is supported by the presence of semiarid to semihumid climates in the source area (Figure 5), and this suggests low chemical maturity.

The ternary plot shows weathering trend illustrated by Al_2O_3 – ($CaO+Na_2O$) – K_2O (Nesbitt and Young, 1984) which is being used to evaluate and correct the effects of K- metasomatism, and gives information on the composition of the fresh source rock (Nesbitt and Young, 1984; Fedo *et al*., 1995). From the A-CN-K ternary diagram (Figure 3), the sediments plotted on the aluminum zone towards kaolinite, confirming intermediate degree of weathering with the exception of one which falls towards CN. This agrees with the earlier interpretation of CIA, CIW, and PIA indices. All samples do not cluster at one point, it may indicate different degree of chemical weathering (differential weathering) which is typical of semiarid and arid climates.

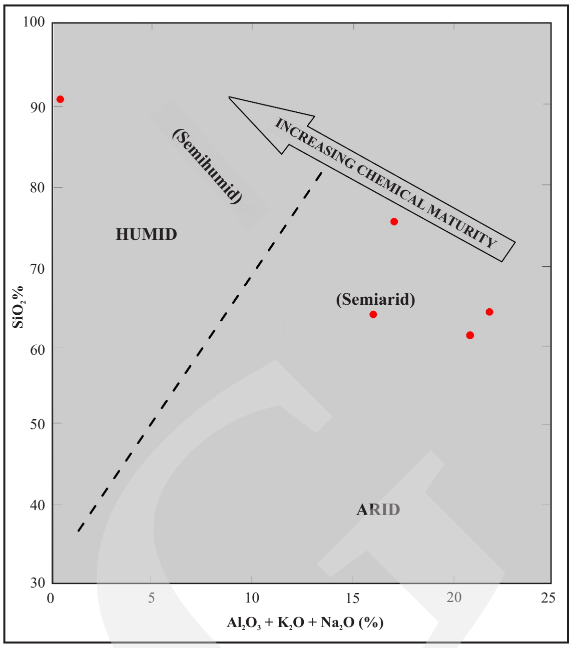

Figure 5. Chemical maturity of the Bida sandstone expressed by bivariate plot of SiO_2 *versus* Al_2O_3+ K_2O + Na_2O; fields after Suttner and Dutta (1986).

Roser and Korsch (1988) proposed a tectonic setting discriminant diagram using log (K_2O/Na_2O) *versus* SiO_2 to differentiate tectonic settings of terrigenous sedimentary rocks. The discrimination diagram identifies three fields: oceanic island arc, active continental margin, and lastly passive margin. All the studied samples are plotted in the passive margin field. Therefore, the studied rocks were probably deposited in the passive margin setting. This is an indication that sediments might have been deposited from one source. The transition between oceanic and continental lithosphere which is not an active plate is a passive margin. It is formed by the accumulation of sediments above an ancient rift which is now marked by the transitional lithosphere. This continental rifting leads to the creation of new subbasins. The continental rift eventually forms a mid-ocean ridge and the locus of extension from the continent down to the ocean-ocean boundary. According to Roser and Korsch (1986), passive margin sediments were largely quartz-rich sediments derived from plate interiors or stable continental areas and deposited in intracratonic basins or on passive continental margins.

The passive margin setting interpretation contradicts with the work of Ikhane *et al*. (2014) in the Niger Delta sediments as the workers attained that the Niger Delta sediments were of the oceanic-island-arc setting.

Conclusions

The major oxide analysis of the sandstone sediments shows the SiO_2, Al_2O, and CaO constitute about 90% of the bulk rock composition, while P_2O_5, Na_2O, K_2O, MgO, TiO_2, MnO, and Fe_2O_3 constitute 10% of the composition. The high concentration of SiO_2, Al_2O, and CaO elements indicates the possibility of silicate and carbonate minerals. Alumina/titania (Al_2O_3/TiO_2) ratios showed that the studied sandstones were derived from intermediate to felsic igneous rocks.

The majority analyzed samples plotted on the aluminum zone towards kaolinite on the A-CN-K ternary diagram have predominantly to intermediate degree of weathering, while one sample that falls towards CN-K line indicates different degree of weathering (differential weathering). This was supported by the presence of semiarid climate in the source region, which was often characterized by topographic effects of differential weathering and erosion. The source area weathering indices which includes CIA, CIW, and PIA further confirmed that the sediments have been subjected to intermediate weathering.

The log K_2O/Na_2O *versus* SiO_2 tectonic setting discriminant plot shows that the samples were dominantly deposited in the passive margin setting. The overall of the studied Bida sandstones were sourced from predominantly felsic igneous rocks, where the degree of chemical weathering in the source area was intermediate, and were deposited on the passive margin setting.

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