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Petrographic and geochemical constraints on petrofacies, provenance and tectonic setting of the upper cretaceous sandstones, Northern Bida Basin, north-central Nigeria

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ABSTRACT

The petrographic and geochemical compositions of the Campanian-Maastrichtian siliciclastic sediments in the northern Bida Basin, North-central Nigeria were investigated with the aim to determine the petrofacies, their provenance and tectonic settings. The mineral composition of the samples selected from the 10 sub-facies in the study area is characterized by abundant quartz (predominantly of monocrystalline quartz) and minor feldspar, rock fragments and heavy minerals. The framework grains are angular, sub-angular to sub-rounded and well sorted with the quartz varieties exhibiting euhedral to subhedral, non-undulose to undulose characteristics. The modal composition reveals the sediments as quartzarenite to sublitharenite with minor sub-arkoses and also reflects felsic rocks derived within passive margin paleotectonics as provenance. Geochemical proxies obtained based on major, trace and rare earth elements data; Al_2O_3/TiO_2, SiO_2/Al_2O_3, K_2O/Al_2O_3, La/Th, La/Co, Th/Co, La/Sc, Cr/Th, Zr/Nb and Zr/Th with chondrite-normalized REE patterns, light REE enrichment, heavy REE flat pattern and negative Eu anomalies revealed sediments derivation mainly from felsic source rocks. A higher Zr/Sc and Zr/Hf ratio with Th/Sc and Zr/Sc binary plot suggest considerable zircon enrichment in the source areas. Discrimination plots; $\log(K_2O/Na_2O)$ versus SiO_2, TiO_2 versus (Fe_2O_3+MgO), Al_2O_3/SiO_2 versus (Fe_2O_3+MgO) and $SiO_2/20$-(K_2O+Na_2O)-$(TiO_2+Fe_2O_3+MgO)$, La/Y versus Sc/Cr, La-Th-Sc, Th-Sc-Zr/10 of the analyzed sandstones suggest that source rocks may lie in the passive continental margin, before sediment transport and deposition in the basin by fluvial modes. This study suggests a passive paleotectonic setting for the Precambrian Basement Complex consisting of two igneous source materials from which the sediments are derived and supplied to the study area.

1. Introduction

Quantitative analysis of siliciclastic sediments using mineralogical, textural and geochemical characteristics has evolved as useful approach for detailed source area reconstructions in sedimentary basin analysis. This is because the sediments composition is controlled primarily by their source, lithology, tectonics, climate, topography, weathering, transport, and depositional environment (Johnsson, 1993). Attempts on provenance studies of a sedimentary rock using framework composition have been made by several workers including Suttner et al. (1981), Dickinson et al. (1983) and Weltje et al. (1998). Bhatia (1983), Roser and Korsch (1986, 1988) and McLennan (1989) had also demonstrated the significance of petrographic and geochemical data for determining source rock provenance and paleotectonic settings.

This present study utilized sedimentological, petrographic, textural and geochemical characteristics of siliciclastic sediments within a large portion of the northern Bida Basin in north-central, Nigeria, to unravel the provenance of Campanian-Maastrichtian sediments and significantly provides the first comprehensive geochemical and petrographic characteristics of the siliciclastic sediments in the area. The Bida Basin is one of the hinterland sedimentary basins in Nigeria with a sedimentary fill of about 4.0 km and it is located between the northern Basement (Central Nigerian Shield) and south-western Basement Complex of Nigeria (West African Shield). The basin is northwest-southeast (NW-SE) trending

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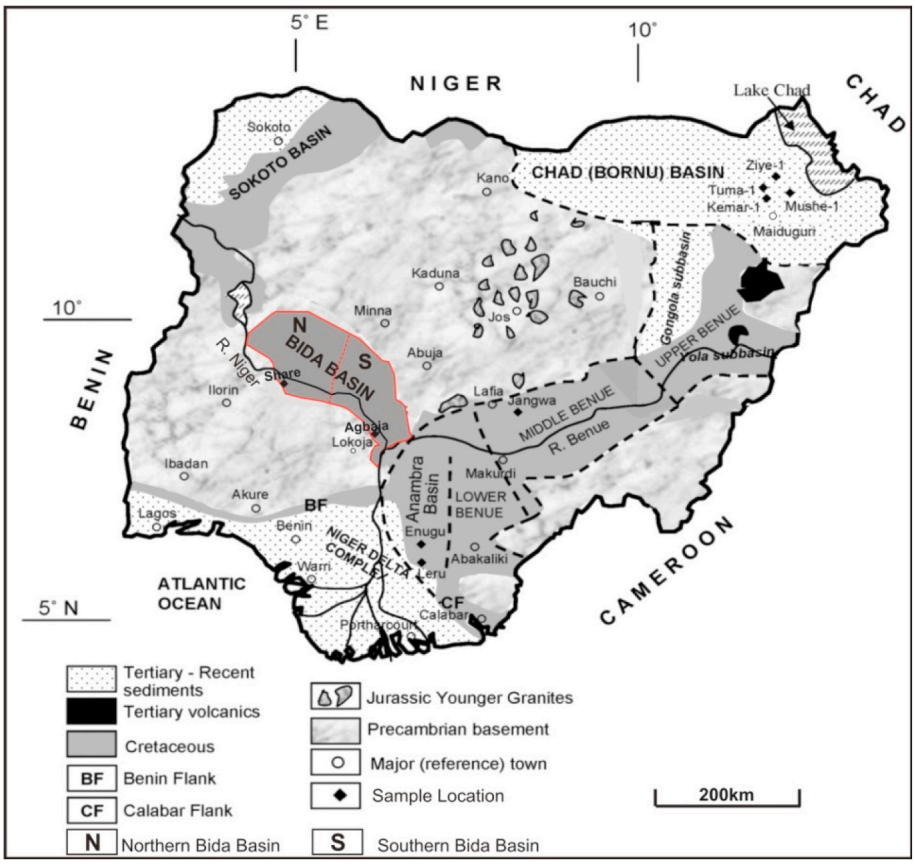


Fig. 1a. Geological map of Nigeria showing the position of the Bida Basin (modified after Obaje et al., 2011).

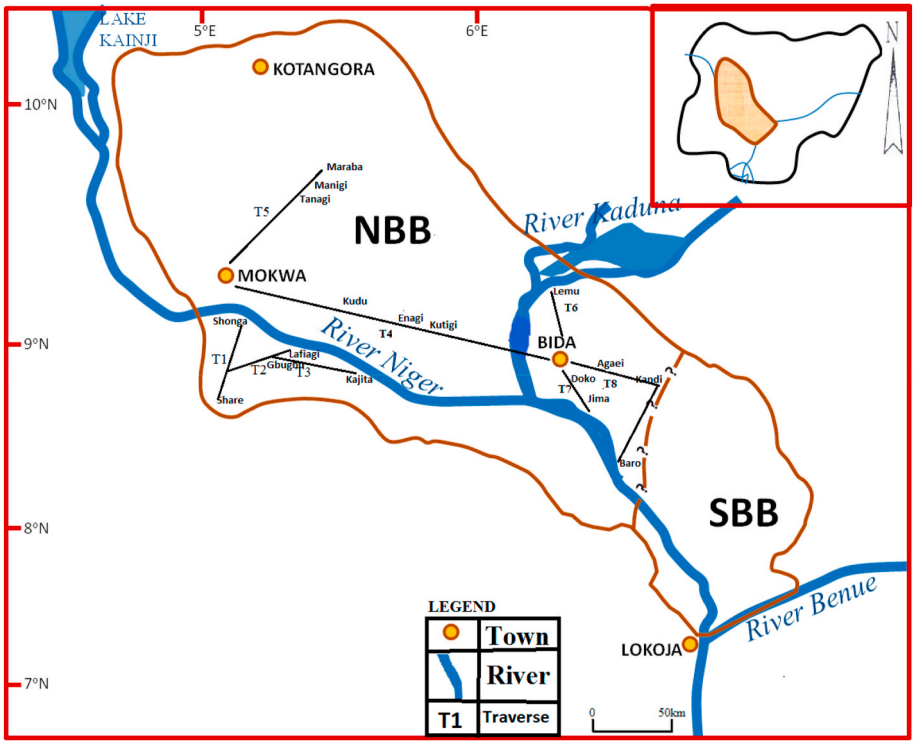


Fig. 1b. Geological map of northern Bida Basin showing the traverses covered in the present study.

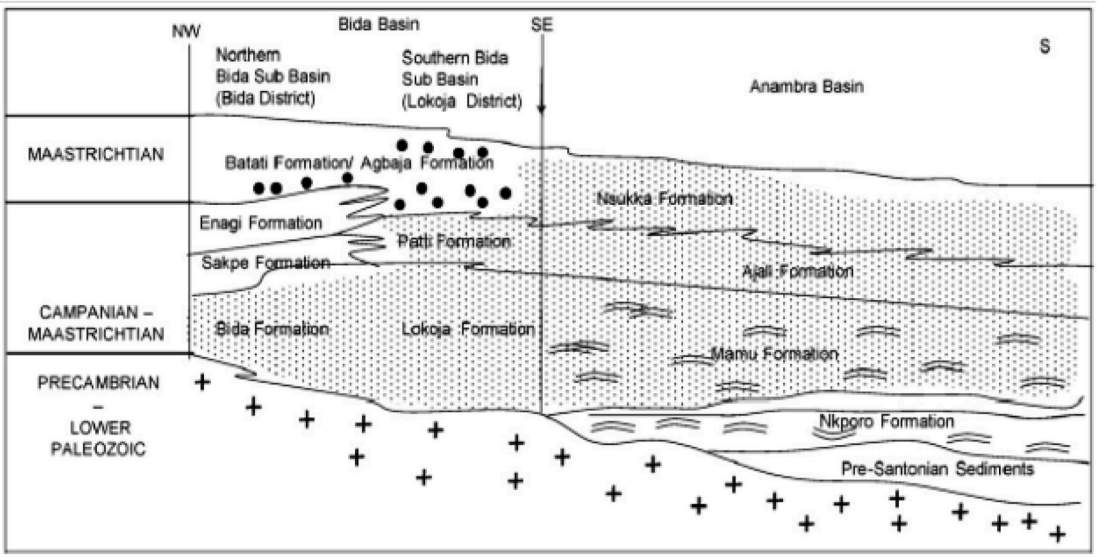


Fig. 2. Regional stratigraphic successions in the Bida Basin and restored NW-SE-S stratigraphic relationships of the Bida Basin to the Anambra Basin (after Ojo and Akande, 2009).

intracratonic type (Fig. 1a) and contiguous with the Sokoto and Anambra Basins in the northwest and southeast covering a territory of approximately 60,000 km^2 and delimited in the northeast and southwest by the Basement Complex (Adeleye (1974).

Significant efforts have been made by several authors in relation to the study of sedimentology, age and petroleum source rock evaluation of the Bida Basin. The earliest worker is Falconer (1911) who described and named the exposures around Kotangora, Lokoja and Patigi as "Lokoja Series". Contributions from Adeleye (1972, 1973 and 1974), Adeleye and Dessauvagie (1972) centers on the stratigraphy and sedimentation of upper Cretaceous succession of the Bida Basin where they defined and established the mappable litho-stratigraphic units that are currently being used for the Bida Basin. Jan du Chene et al. (1978) documented the palynomorph-foraminifera associations for the interpretation of the paleoenvironments of the Lokoja and Patti Formations. Ojo and Akande (2009) interpreted the paleoenvironments of the sedimentary successions in the southern Bida Basin as ranging from continental to marginal marine and marsh environments for the Cretaceous lithofacies. Ojo and Akande (2008) and Ojo (2010) investigated the palynomorphs assemblages and paleoenvironments of the Patti Formation and dated the shaly facies as Maastrichtian age. Efforts were also made by Obaje et al. (2004, 2005, 2011, 2013), Ojo et al. (2018) on the evaluation of the hydrocarbon prospectivity of the basin and reported availability of hydrocarbon source rocks. Meanwhile, only few research works have been carried out in the Northern Bida Basin and published; Olaniyan and Olobaniyi (1995) who attempted and studied aspects of sedimentology and stratigraphy of north of Niger River suggested fluvial environments for the sandstones and the conglomerates. Ojo (2012) deduced fluvial processes for Bida Formation sediments around Share-Patigi area and concluded that subarkose facies of short transportation history were prevalent in an uplifted continental block provenance of warm humid paleoclimatic conditions. This paper provides clear deductions about the compositional characteristics, provenance, tectonic setting in a regional scale in the northern Bida Basin.

2. Geological and regional stratigraphic settings

The northwest southeast trending Bida Basin which is also known as Nupe and/or Mid Niger Basin is an inland sedimentary basin, located in the north central part of Nigeria (Ojo, 2012). It is a shallow depression filled with estimated 3500 m thick clastic sediments that are largely flat bedded (Udensi and Osazuwa, 2004). The geological framework in terms of evolutional and structural pattern has been presented in many published works. The workers include; King (1950) and Kennedy (1965) who interpreted the basin as rift bounded tensional structure associated with the larger Benue Trough system which evolved during the early Cretaceous separation of Africa and South America plates. The findings from related studies (Kogbe et al., 1983; Ojo and Ajakaiye 1989) showed major NW/SE trending faults and existence of deep seated central positive anomaly flanked by negative anomalies in the basin and these supported rift theory. On the other hand, Adeleye (1974) and Whiteman (1982) suggested the idea of simple post Santonian cratonic sag.

The stratigraphic framework of the Upper Cretaceous Bida Basin has been discussed in several published work among which are the work of Adeleye and Dessauvagie (1972) and Adeleye (1973). In order to simplify the stratigraphic framework, they sub-divided the basins into two arms (Fig. 2); northern and southern Bida basins each with distinct mappable stratigraphic entities. Agyingi (1993) and Ojo and Akande (2008, 2008) presented a detail description of the stratigraphic succession in the southern Bida Basin.

The Bida Formation is the lateral correlation of the Lokoja Formation in the northern part of the Basin. It comprises of two members; the Doko member is about 183 m thick while the Jima member is about 90 m thick according to Adeleye (1972). The Doko member is the basal unit and consists mainly of very poorly sorted pebbly arkose, sub-arkose and quartzose sandstones and thought to have been deposited in a braided alluvial fan setting based on the submission by Adeleye (1972). The Jima sandstone member is dominated by cross-stratified quartzose sandstones, siltstones and claystones. Trace fossils comprising mainly of *Ophiomorpha*, *Thalassinoides* have been observed by Adeleye (1972). Sedimentological evidence from the study by Whiteman (1982) indicates deposition in a braided stream environment for the Doko sandstone member, while Jima member is deposited under lower stream energy. Indication of channel margin deposit under tropical to subtropical conditions was suggested by Adeleye (1973) whereas Adeleye and Dessauvagie (1972) used evidence of leaf impression to assigned late Cretaceous age (Campanian-Maastrichtian).

The Sakpe Formation overlies Bida Formation and comprises mainly of oolitic and pisolitic ironstones with sandy claystones locally at the base, followed by dominantly oolitic ironstone which exhibits rapid facies changes across the basin, at the top (Adeleye, 1972). According to Adeleye (1973), it comprises two members; Wuya and Baro ironstone. The Wuya Ironstone comprises mainly of oolitic and pisolitic ironstones with subsidiary sandy claystone locally present at the base with

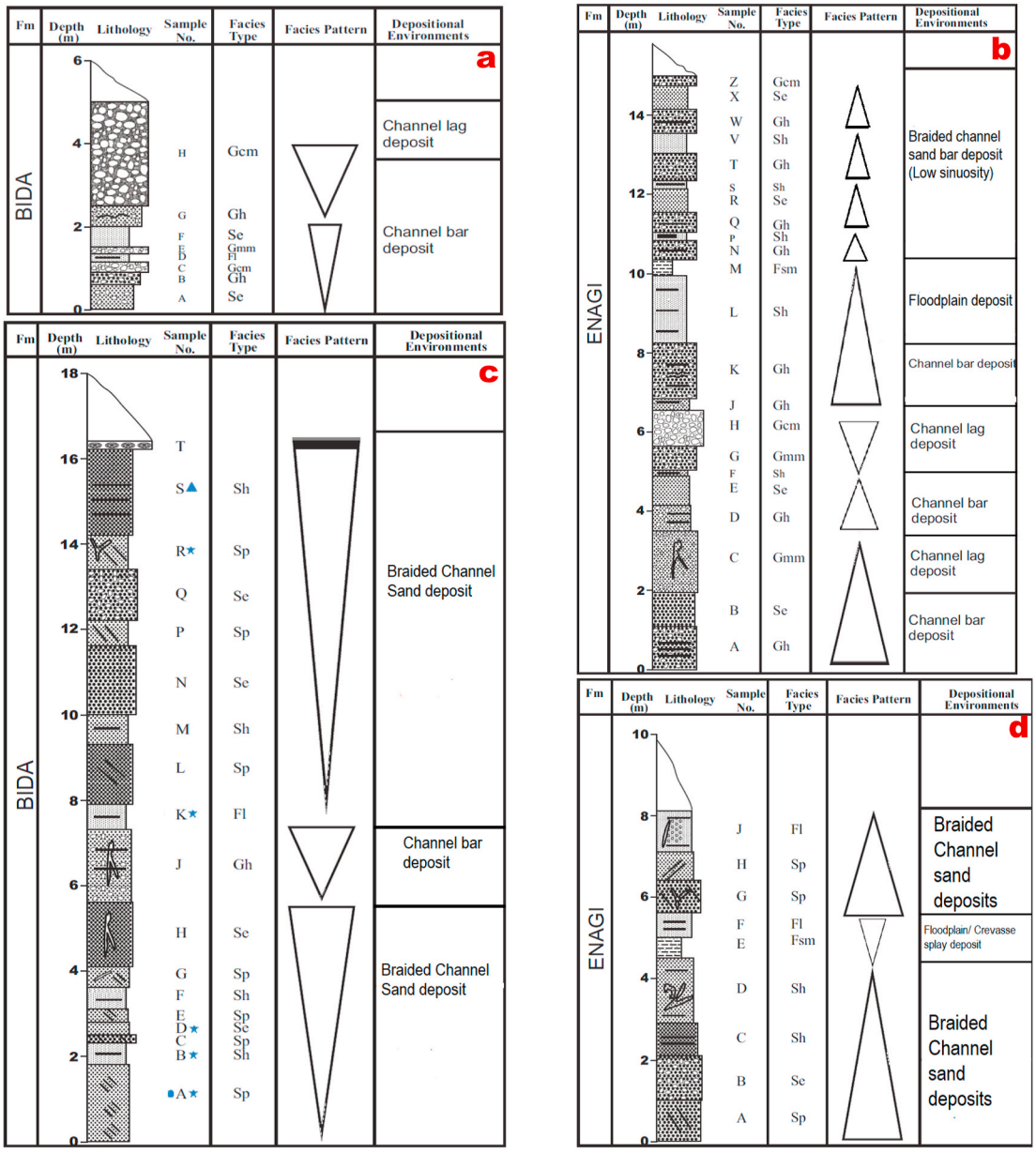


Fig. 3. Lithological sections of (a) Bida and Formation exposed at (a) Baganko & (b) Bida and Enagi Formation exposed at (c) Tshonga & (d) Tanagi.

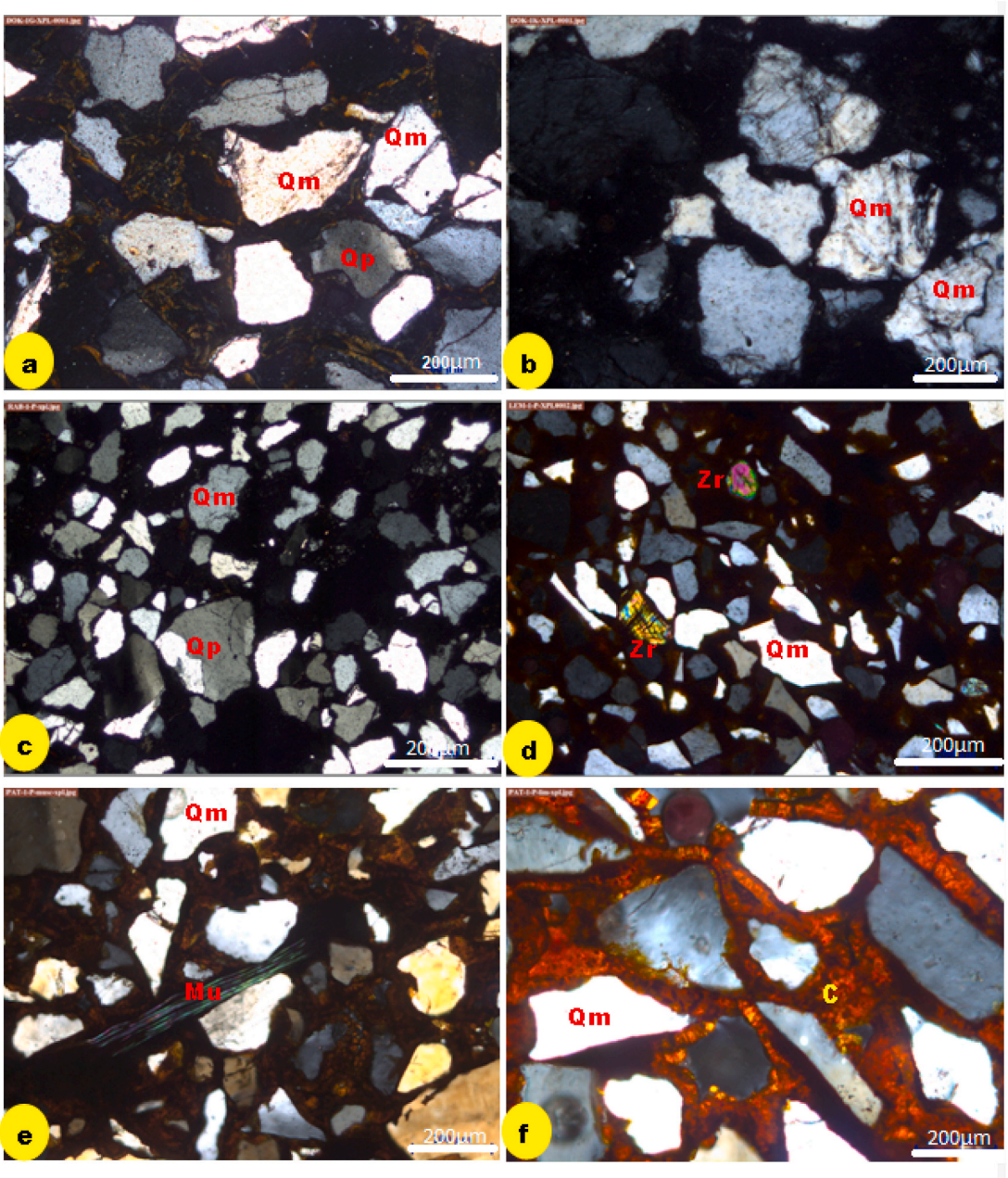


Fig. 4. Photomicrographs of typical (a) crudely bedded conglomerate (Gh) sub-facies (DOK-1G), (b & c) horizontally stratified sandstone (Sh) sub-facies (DOK-1K and RAB-1P), (d) finely laminated, very-fne sandstone and mudstone (Fl) sub-facies (LEM-1P) and (e & f) planar cross-stratified sandstone (Sp) sub-facies (PAT-1N) showing the mineral constituents; Qm (monocrystalline quartz), Qp (polycrystalline quartz), Zr (zircon), Mu (Muscovite) and C (Cement) on cross polarized light (XPL).

Table 1
Lithofacies and sub-facies types in the study area.

Lithofacies	Sub-facies Code (after Miall (1988a,b and 1992))	Description	Location
Conglomerate	Clast Supported Conglomerate (Gcm)	Massive, poorly sorted, clast-supported, imbricated conglomerate.	Patigi, Baganko, Ndeji, Shonga
	Matrix Supported Conglomerate (Gmm)	Massive, poorly sorted, subrounded to subangular conglomerate.	Patigi, Baganko, Lade, Share town, Shonga, PattiChin and Baro
	Crudely bedded Conglomerate (Gh)	Weakly laminated, poorly sorted, very coarse-pebbly sandstone.	Shonga, Zambufu, Gbugbu, Wariku, Lafiagi, Baganko, Baro
Sandstone	Crudely bedded Sandstone (Se)	Weakly bedded sandstone (fine to very coarse grained).	Share, Shonga, Rabba, Bida, Enagi, Wushishi, Baro, Lemu and Doko
	Planar cross-bedded sandstone (Sp)	Planar cross bedded sandstone (fine to very coarse grained).	Kutigi, Jima, Doko, Kajita, Bida, Tanagi Rabba
	Rippled cross-bedded sandstone (Sr)	Rippled cross-bedded sandstone (fine to very coarse grained).	Share, Wariku, Rabba
	Horizontally stratified sandstone (Sh)	Planar laminated sandstone (fine to very coarse grained).	Rabba, Bida, Kutigi, Tanagi, Manigi, Maraba, Lemu, Doko, Jima
	Massive sandstone (Sm)	Massive sandstone (fine to very coarse grained).	Share, Shonga, Jima, Doko, Kajita, Enagi, Lemu, Lafiagi, Rabba

thickness of about 5 m at the type locality. The Baro ironstone member consists of oolitic ironstone and ferruginous sandstone which are locally pyritic and concretionary.

Enagi Formation was concluded by Adeleye (1973) to consist of siltstone with subordinate amounts of sandstones, siltstone-sandstone admixtures and claystone and correlates with the Patti Formation in the southern Bida sub-Basin. It occurs just below the tops of the major mesas such as the Doko plateau. Other lithofacies that can also be found include sandstone-siltstone intercalation and claystones. Maastrichtian age is assigned by Adeleye (1973) because of its stratigraphic position between the Sakpe ironstone and Batati ironstone. Adeleye (1973) suggested a fluviatile depositional environment which he stated was as a result of the withdrawal of the Tethys northwards.

Batati Formation is the youngest Cretaceous unit in the northern part and it is laterally correlated with the Agbaja Formation in the southern Bida Basin. It consists of argillaceous, oolitic and goethitic ironstones with ferruginous claystone and siltstone intercalations and shaly beds occurring in minor proportions, some of which have yielded nearshore shallow marine to fresh water fauna (Adeleye, 1973). Braide (1992) interpreted the sedimentary paleoenvironment based on lithofacies suggested a meandering fluvial environment developed from alluvial fans and braided fluvial channels in poorly drained flood plains.

3. Materials and methods

Logging and sampling exercise was carried out on twenty well exposed lithological sections (Fig. 3). The surface outcrops sections were logged and beds were measured using measuring tapes and relevant information was recorded. A composite stratigraphic profile of the strata was also constructed where necessary and fresh representative samples collected at different depth and horizons from the bottom to the top of each vertical profile of the exposed sections. The samples were thereafter stored properly in the sample bags and labelled for laboratory analysis.

A total number of seventy-five (75) well-consolidated sandstones samples were selected based on the facies for petrographic (thin section) analysis (Appendix A). Rock thin-section preparation and studies were accomplished in the thin section workshop and microscope laboratory respectively at the National Geophysical Research Institute (NGRI), Hyderabad, India using standard procedure for petrological studies. In the laboratory, a rock saw was used to cut the sandstone samples into chips, suitable for standard 27 by 46 mm thin sections before study under the NIKKON polarizing microscope where standard petrological techniques were employed in description. Petrographic study of the detrital minerals involves determination of framework composition, authigenic components, cement-grain relationship and diagenetic signatures. Mineralogical compositions of each sample was determined by compositional modal analysis following the traditional method and conventional point-count which minimizes the control of grain size on sand composition according to Gazzi (1966), Dickinson (1970) and Ingersoll et al. (1984). The categories of identified grain types include; quartz (monocrystalline and polycrystalline), feldspar (potassium and plagioclase), sedimentary lithics or rock fragments and opaque minerals (iron-rich minerals). The resulting grain composition data were compiled and the three end members (quartz, feldspar, and lithics/rock fragments) were re-calculated to percentage to obtain framework composition (monocrystalline quartz-Qmand polycrystalline quartz-Qp; plagioclase feldspar-P and potassium feldspar-K; , sedimentary lithic fragments-Ls, volcanic lithic fragments-Lv and metamorphic lithic fragments-Lm) in order to determine the trends of compositional change over time (Appendix B, supplementary materials).

Representative samples (sandstones and siltstones) were also selected for the bulk geochemical analysis from the collected samples based on the facies variations following standard techniques by Tucker (1996). Forty-six (46) samples (Appendix C, supplementary materials) were selected for major elemental compositions using X-ray fluorescence (XRF) while seventy-four (74) rock samples (Appendix E and G, supplementary materials) were selected for trace and rare earth elements using Laser Ablation Multicollector Inductive Coupled Mass Plasma Spectrometer (LAM-MC-ICPMS) at the National Geophysical Research Institute (NGRI), Hyderabad, India. Prior to analysis, about 50–100 g of the whole rock samples were reduced to chips of 2–4 mm and pulverized in a mortal agate mill to avoid contamination. For the determination of major elements, selected samples were made into pellet in the XRF laboratory whereas for the trace and rare elements analysis, 50.0 mg of each samples was digested with mixture of 3.0 ml of concentrated hydrogen fluoride (HF), 1.0 ml of concentrated hydrogen nitrate (HNO_3) and 1.0 ml of concentrated hydrogen per chlorate

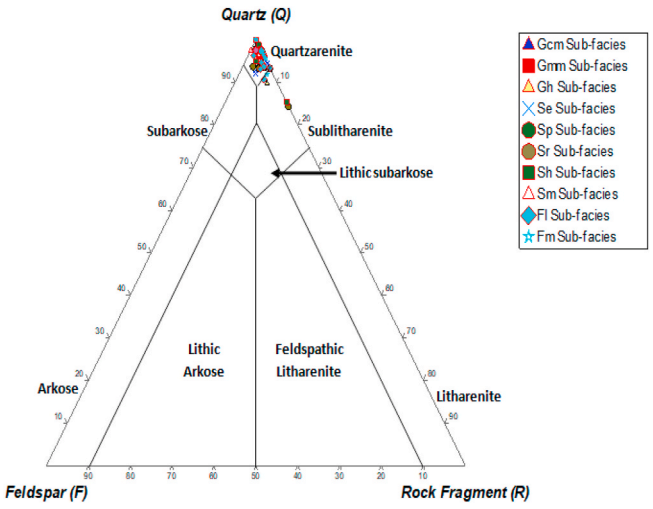


Fig. 5a. Standard Ternary petrographic classification of studied sandstones using framework composition of Quartz-Feldspar-Rock Fragment (Q-F-R) after McBride (1963).

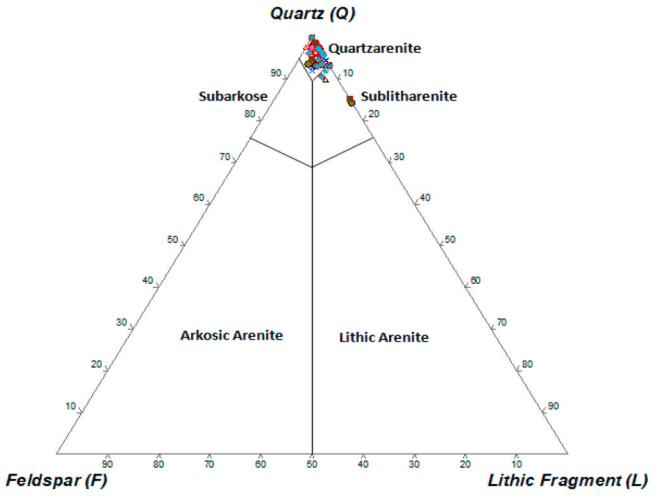


Fig. 5b. Standard Ternary petrographic classification of studied sandstones using framework composition of Quartz-Feldspar-Lithic Fragment (Q-F-L) after Pettijohn (1975).

($HClO_4$) for 48 h in a tightly closed Teflon vessel on a hot plate at temperature <150 °C. Later, the solution was evaporated to dryness and extracted with 60.0 ml of 1% HNO_3. Replicate analyses of samples and standards indicate that errors for major elements vary between 1 and 2%. Each sample was run against an internationally recognized standard reference material (SRMs) viz., GSR 4, GSR 6, GXR-6 to correct long-term instrument drift. The rare earth elements data were normalized relative to the Chondrite (Cl) after (Boynton, 1984), Post Archean Australian Shale (PAAS) after McLennan (2001), Upper Continental Crust (UCC) after McLennan (1989) and North American Shale Composite (NASC) after Gromet et al. (1984) values. Accuracy of the trace and REE element analyses is within 5%.

4. Data presentation and results discussion

4.1. Facies analysis

Field observation and lithofacies classification is a standard tool of facies-analysis (Miall, 1996). In this study, the established lithological variations were employed in interpreting facies analysis. Facies analysis

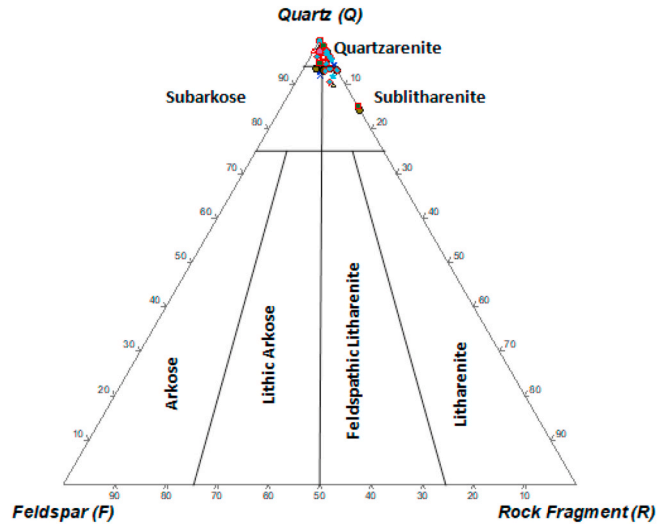


Fig. 5c. Standard Ternary petrographic classification of studied sandstones using framework composition of Quartz-Feldspar-Rock Fragment (Q-F-R) after Folk (1980).

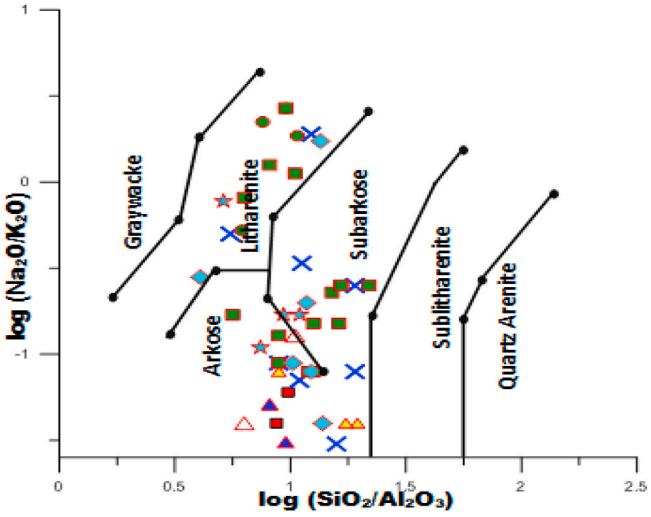


Fig. 5d. Bivariate geochemical classification of the studied sandstones using $\log(SiO_2/Al_2O_3)$ versus $\log(Na_2O/K_2O)$ after Pettijohn et al. (1973).

involves the detail measurement, description and record of vertical and lateral lithological sections within the study area Miall (1977). Three (3) lithofacies and ten (10) sub-facies were delineated from this study (Table 1 and Fig. 3) and the details presented in Adepoju (2019). It is important to note that the samples analyzed were selected on the basis of the facies delineated.

4.2. Petrography and mineralogical composition

The petrographic components and modal composition of the minerals is discussed here with the aim to identify the compositional variations across the study area. The detrital mineral description of the components revealed the following minerals: quartz, feldspars, rock fragments, micas, cements (iron, clay and silica) and heavy minerals. Framework composition of the mineral constituents from the petrographic study and the recalculated framework constituents to 100 percentage of the three important detrital (quartz, feldspar and lithic fragments) with their varieties is presented in Appendix A (supplementary materials).

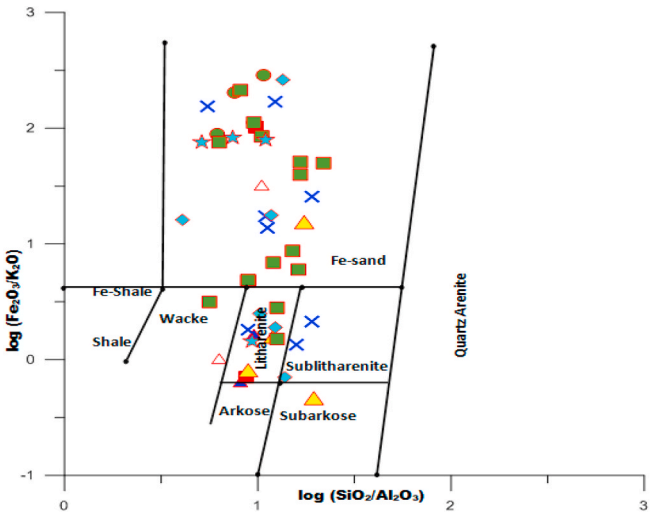


Fig. 5e. Bivariate geochemical classification of the studied sandstones using $\log(SiO_2/Al_2O_3)$ versus $\log(Fe_2O_3/K_2O)$ after Herron (1988).

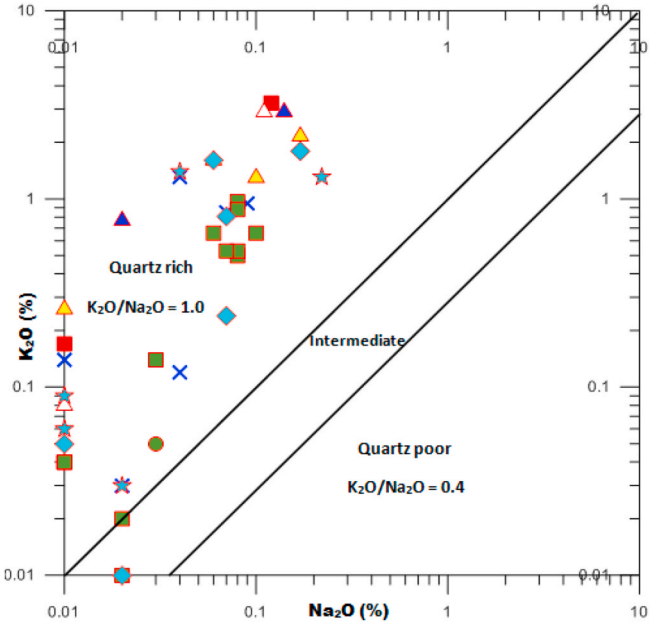


Fig. 5f. Bivariate geochemical classification of the studied sandstones using K_2O (%) versus Na_2O (%) after Crook (1974).

The modal analysis of the sub-facies show the framework compositions as follows; crudely bedded conglomerate (Gh) sub-facies: (Qt) 77–80%, feldspar (F) 0–2% and lithic/rock fragments (L/R) 2–6%, crudely stratified Sandstone (Se) sub-facies: (Qt) 68–82%, feldspars (F) 0–3% and total lithic/rock fragments (L/R) 2–6%, planar cross-stratified sandstone (Sp) sub-facies: (Q) 65–85%, feldspar (F) 0–3% and total lithic/rock fragments (L/R) 1–12%. rippled cross -stratified Sandstone (Sr) sub-facies: (Q) 81–83%, feldspar (1–2%) and lithic/rock fragments (1%), horizontally stratified sandstone (Sh) sub-facies: (Q) 58–87%, feldspar (0–2%) and rock fragments (0–10%), massive sandstone (Sm) sub-facies: (Q) 78–85%, feldspar (F) 1–2% and total lithic/rock fragments (Lt) 0–2%, finely laminated, very-fine sandstone and mudstone (Fl) sub-facies, (Qt) 68–83%, total feldspar (F) 0–2% and lithic/rock fragments (Lt) 1–5%, massive, very-fine sandstone and mudstone (Fm) sub-facies: (Q) 68–85%, feldspar (F) 0–1% and lithic/rock fragments (L/R) 0–5% (Appendix B, supplementary materials).

Generally, for all the sub-facies, quartz is the dominant detrital

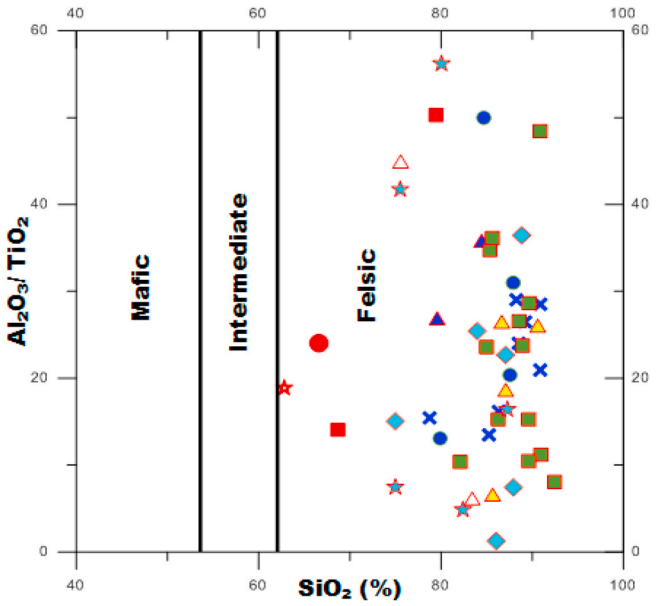


Fig. 6a. Bivariate Al_2O_3/TiO_2 versus SiO_2 provenance discrimination plot after Le Bas et al. (1986) showing Felsic field as source for the studied sandstones.

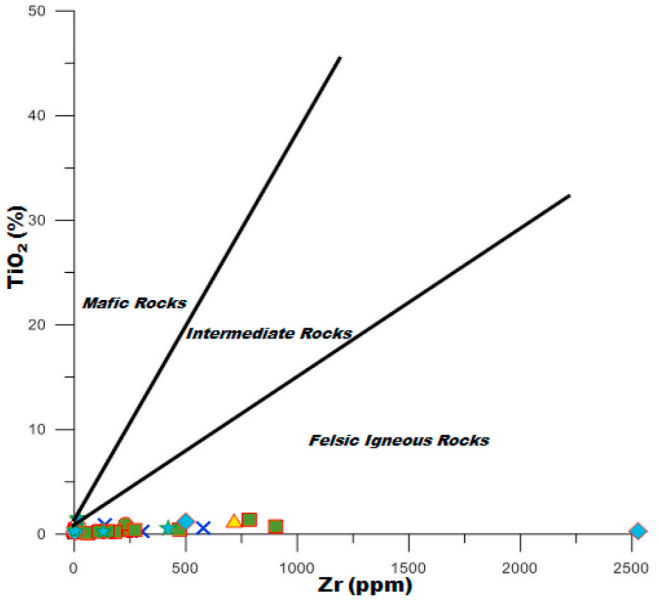


Fig. 6b. Bivariate TiO_2 versus Zr (ppm) provenance discrimination plot after Hayashi et al. (1997) showing studied sandstones sediments derivation from felsic Igneous Rocks.

mineral with higher proportions of monocrystalline (Qm) than polycrystalline (Qp) varieties and both exhibit euhedral to subhedral, very angular to sub-angular and non-undulose to undulose types (Fig. 4a and b). Meanwhile, few fractured polycrystalline quartz grains (Qp) also present (Fig. 4a and b). Feldspars which is next in abundance in the framework composition have more microcline than plagioclase varieties, and the lithic fragments occur observed in minor proportions. The matrix present is clay and silt while the identified dominating cementing minerals are kaolinite and or iron-oxide (limonite, goethite and hematite) which often form as a coatings and rims around the framework grains (Fig. 4f). Muscovite is also observed in few samples (Fig. 4e) while heavy minerals like zircon also observed in minor amounts in the framework (Fig. 4d).

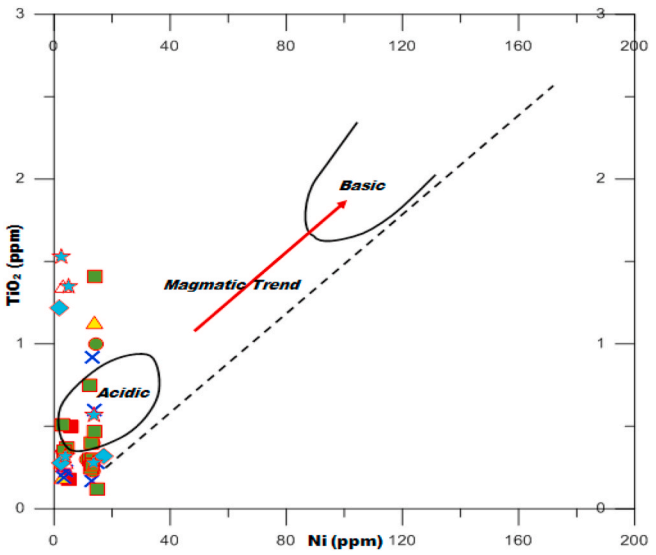


Fig. 6c. Bivariate TiO_2 (%) versus Ni (ppm) provenance discrimination plot showing acidic rocks for studied sandstones after Floyd et al. (1989).

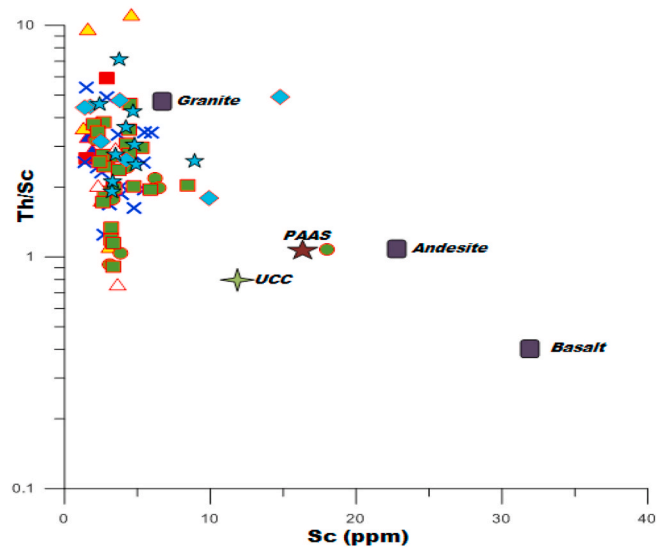


Fig. 6e. Bivariate Th/Sc versus Sc provenance discrimination plot for the studied sandstone; PAAS (Taylor and McLennan, 1985), UCC (McLennan, 2001) and granite, andesite, and basalt (Condie and Wronkiewicz, 1990).

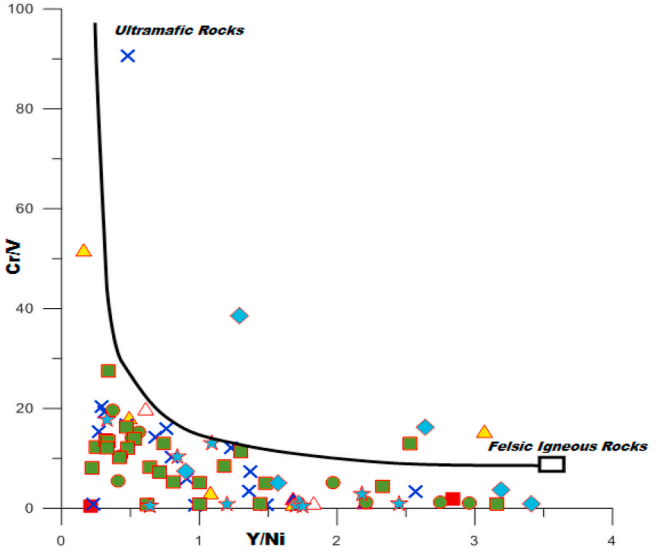


Fig. 6d. Bivariate Y/Ni versus Cr/V provenance discrimination plot after Floyd et al. (1990) and Hayashi et al. (1997) showing felsic Igneous Rocks derivation for the studied sandstones.

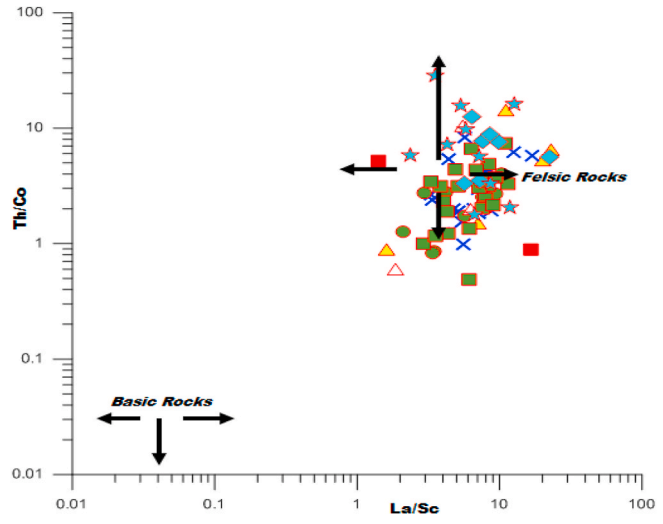


Fig. 6f. Bivariate Th/Co versus La/Sc provenance discrimination plot for the studied sandstone after Mclennan and Taylor (1991) and Cullers (2002).

4.3. Geochemical data

The geochemical data; major, trace and rare earth elements of the studied sediments and their statistical relationships are presents in Appendices C to H (supplementary materials). Major elements result shows that SiO_2 is the dominating element while Al_2O_3, Na_2O, K_2O, Fe_2O_3 and MnO are generally comparably less except in few samples. Relative high content of Fe_2O_3 in some sediment may indicate part of the sediments was possibly precipitated as iron-rich minerals during sedimentation and/or diagenesis. The results were also compared with the published values of average Upper Continental Crust (UCC) after McLennan (1989) and Post-Archean Australian Shale (PAAS) after McLennan (2001). Also, the trace and rare earth elements concentrations (variations and ranges) of the studied sediments as well as the compared standard values are presented in Appendices E and G (supplementary materials).

4.4. Sediment classification

Reviewed literature indicates modal compositional data (Petrographic and geochemical) has been employed by many researchers for clastic sedimentary rocks petrofacies studies in order to understand their provenance and interprete the tectonic settings. Dickinson and Rich (1972), Dorsey (1988) with Critelli and Ingersoll (1995) concluded that detrital composition of sandstone can furnish vital clues regarding the source rock composition, its tectonic setup, role of climate, relief, transport and diagenesis, hence, it is necessary to synthesize the petrofacies for a logical identification of provenance. Many authors; Crook (1974), Pettijohn et al. (1973), Blatt et al. (1980), Herron (1988) have also classified sandstones based on their chemical composition, but it is stated that geochemical classification of sandstones does not mimic conventional mineralogical composition of sandstones based upon quartz-feldspar-lithic fragment; rather differentiate between mature and immature sedimentary rocks.

For the purpose of classification and petrofacies of the studied

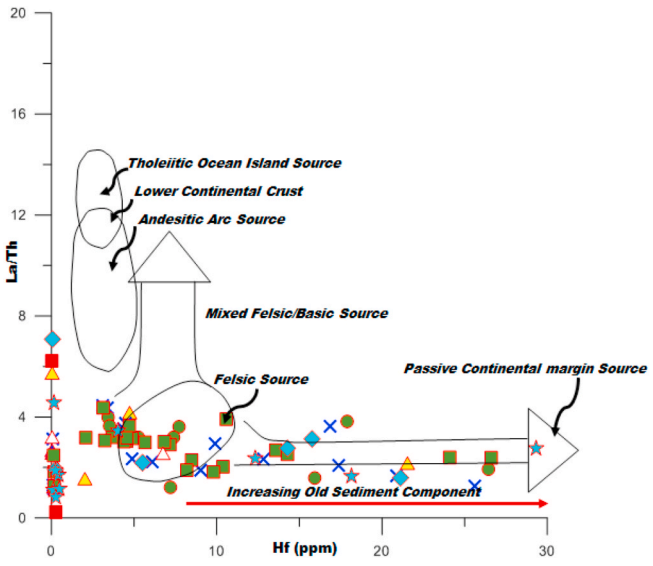


Fig. 6g. Bivariate provenance discrimination plot using La/Th versus Hf after Floyd et al. (1990) and Hayashi et al. (1997) showing felsic igneous rocks derivation for the studied sandstone.

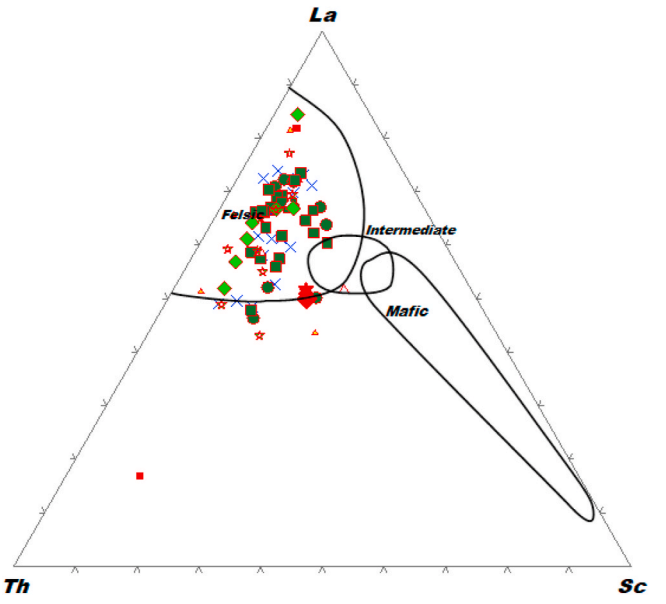


Fig. 6i. Standard La-Th-Sc Ternary discrimination plot showing Felsic field for the studied sandstones after Cullers (2002).

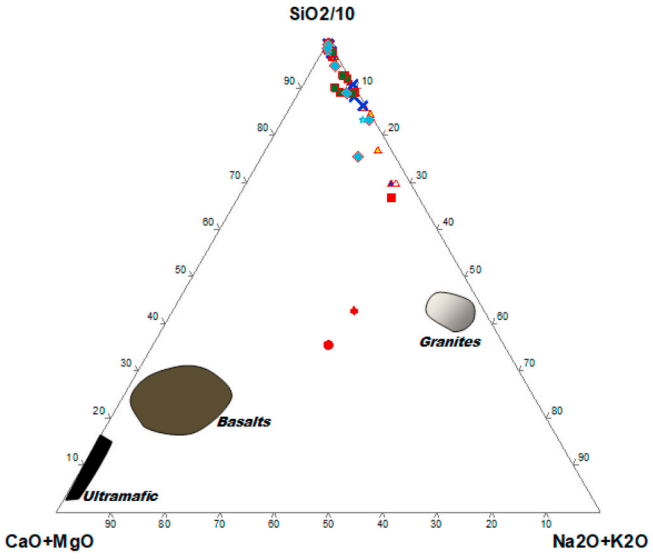


Fig. 6h. The standard SiO_2/10-CaO+MgO-Na_2O+K_2O ternary provenance discrimination plot after Taylor and McLennan (1985) showing granites fields as the source for the studied sandstones.

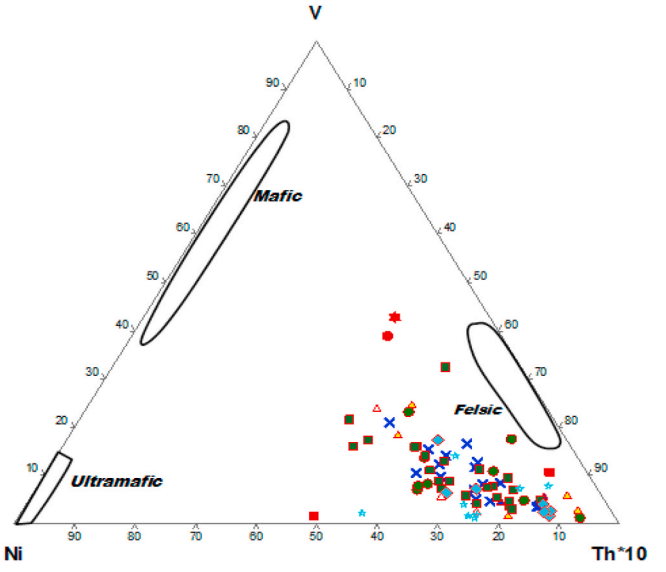


Fig. 6j. The standard V-Ni-Th*10 ternary provenance discrimination plot after Bracciali et al. (2007) showing Felsic fields as the source for the studied sandstones.

sediments, results of the recalculated (100%) three-end members; quartz (Q), feldspar (F) and lithic or rock fragment (L/R) compositions to determine the framework components of sub-facies presented in T Appendix B (supplementary materials) is employed; crudely bedded conglomerate (Gh) - $Q_{91.89\text{-}100}F_{0\text{-}1.35}L/R_{0\text{-}5.76}$, crudely stratified sandstone (Se) - $Q_{92.11\text{-}97.62}F_{0\text{-}3.95}L/R_{2.38\text{-}4.56}$, planar cross-stratified sandstone (Sp) - $Q_{84.42\text{-}98.84}F_{0\text{-}3.75}L/R_{1.15\text{-}14.58}$, rippled cross-stratified sandstone (Sr) - $Q_{97.59\text{-}97.65}F_{1.18\text{-}1.20}L/R_{1.18\text{-}1.20}$, horizontally stratified sandstone (Sh) - $Q_{84.29\text{-}100}F_{0\text{-}2.5}L/R_{0\text{-}14.71}$, massive sandstone (Sm) - $Q_{95.3\text{-}95.65}F_{1.14\text{-}2.38}L/R_{0\text{-}2}$, finely laminated, very-fine sandstone and mudstone (Fl) - $Q_{90.67\text{-}97.65}F_{0\text{-}2.67}L/R_{1.20\text{-}5.67}$ and massive very-fine sandstone and mudstone (Fm) - $Q_{91.89\text{-}100}F_{0\text{-}1.35}L/R_{0\text{-}5.75}$. The modal composition above was then plotted on the Quartz-Feldspar-Lithic/Rock fragment ternary diagrams; Q-F-R after McBride (1963), Q-F-L after Pettijohn (1975) and Q-F-R diagram after Folk (1980) schemes and the sediments are classified as quartzarenite to sublitharenite with minor sub-arkoses (Fig. 5a, b and c). Also, classification based on the application of rock geochemistry, like petrographic compositional data was also made. This classification scheme popularly referred to "SandClass" employed log(Na_2O/K_2O) versus log(SiO_2/Al_2O_3) after Pettijohn et al. (1973), log(Fe_2O_3/K_2O) versus log(SiO_2/Al_2O_3) after Herron (1988) and K_2O(%) versus Na_2O(%) after Crook (1974) and its applications in this study revealed that the quartz-rich sandstones were geochemically classified as Fe-sand, litharenite, sublitharenite, arkose and subarkose and wacke sandstone types (Fig. 5d, e and f) (see Fig. 6).

4.5. Provenance

Provenance study using mineralogical composition and relative abundances is based on the assumption that detrital grain compositions have not been altered significantly by sedimentary processes and the

intention is to reconstruct and interprete the history of sediment from the initial erosion of parent rocks to the final burial of their detritus (Weltje and Eynatten, 2004). The detrital quartz is a chemically and physically durable and most abundant mineralogical constituent of framework and has been used as a useful guide to provenance determination (Folk, 1980). Conclusions from independent studies by Ingersoll et al. (1984) and Carozzi (1993) have shown that sandstone's petrographic analysis is one of the most commonly used techniques in studying provenance history of sediments, because the mineralogical composition of sandstone grains is key in the study of provenance. Many types of quartz grains have been distinguished based on criteria such as the shape and number of sub-crystals present in the grain and their extinction behaviour when the microscope stage is rotated under crossed polars; some of these quartz grains are associated with specific types of source rocks (Scholle, 1979; Blatt et al., 1980).

The result of mineralogical composition presented in Appendix B (supplementary materials) shows that monocrystalline quartz with non-undulose and straight extinction is the predominant compare to the polycrystalline varieties in all the sandstone sub-facies. Scholle (1979) concluded that monocrystalline grains with straight extinction are common in quartz of igneous origin while polycrystalline quartz with crystal boundaries is characteristic of quartz from a metamorphic source. Conclusions from Basu et al. (1975), Basu (1985) and Blatt et al. (1980) also confirmed that predominance of non-undulose monocrystalline quartz indicates a granitic provenance which is consistent with the provenance definition of Basu (1976), therefore this implies that the studied sediments were sourced from the granitic crystalline basement provenance. Feldspar clasts were partly altered where present or even absence (in some cases). However, where present, potassic varieties (K-feldspar) occur as the dominant over the plagioclase types and this suggest mainly derivation from granitic provenance (Basu, 1976; Datta, 2005). The rock fragment in sandstone framework is among the most informative of all detrital components in diagnosing and determining the provenance composition (Pettijohn et al., 1973). The low percentages of lithic fragments and matrix compared to the rest framework composition in the studied sediments signify features of compositionally mature sandstones.

Based on the composition and detrital modal compositions of the sediments in the study area, the sandstones are classified as quartzarenite and sublitharenite with minor sub-arkoses. The detrital composition modes show that quartzarenite sandstone are characterized by abundant monocrystalline quartz and generally lack plagioclase, while sublitharenite composed more monocrystalline with few polycrystalline quartz. Change in sandstone petrofacies (Fig. 3a, b and c) shown by compositional change over the area may points to a shifts and change in the rate of contributions from the source. Generally, occurrence of higher monocrystalline quartz grains with strong undulatory extinction and low polycrystalline quartz (Appendix B, supplementary materials and Fig. 4) in this study are suggestive of igneous source origin according to Blatt et al. (1980). Also, high ratio of monocrystalline to polycrystalline quartz grains (Qm/Qp) may supports sediments' derivation from a granitic source as suggested by Basu et al. (1975). Minor amount of sedimentary lithic fragments may suggest minimal reworking and rapid localized deposition. Conversely evidence of igneous lithic fragment shown in Appendix B (supplementary materials) and Fig. 4 may indicate some reworking from a Basement Complex provenance. The muscovite grains shown in Fig. 3e may indicate a nearby granitic source area.

The geochemical characteristics of clastic sedimentary rocks have been used to decipher the provenance of the source region (Taylor and McLennan, 1985; Condie et al., 1992). Potter (1978), Yamamoto et al. (1986), Sugitani et al. (1996), and Condie and Wronkiewicz (1990) concluded that Al_2O_3 and TiO_2 contents of the siliciclastic sedimentary rocks and their ratios (SiO_2/Al_2O_3) are considered as significant indicators of their provenance. Hayashi et al. (1997) suggested that the ratio of Al_2O_3/TiO_2 can be used to determine sediments source area

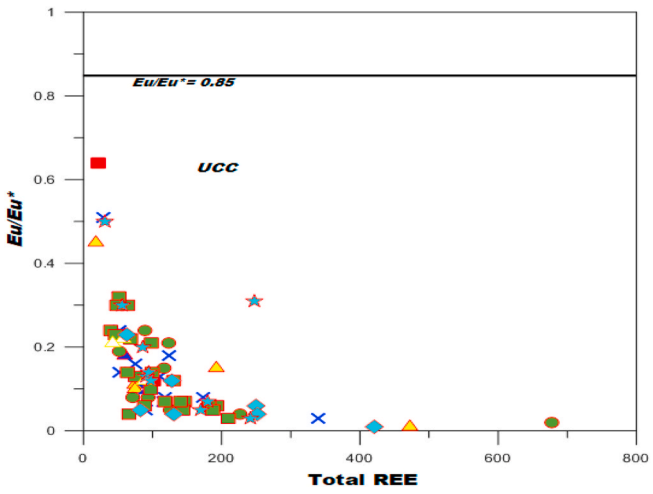


Fig. 7a. Bivariate Total REE versus Eu/Eu* provenance variation plot showing fractionation relationship for the studied sandstone after McLennan (1989).

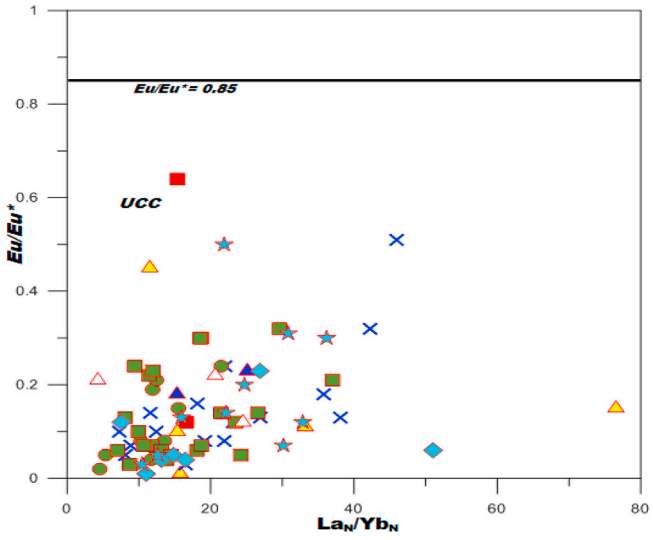


Fig. 7b. Bivariate La_N/Yb_N versus Eu/Eu* provenance variation plot showing fractionation relationship for the studied sandstones after McLennan (1989).

especially the fluvially transported detrital siliciclastic material as they are always similar to those of their source. He stated that the mafic igneous rocks is suggested to have Al_2O_3/TiO_2 ratio ranging from 3 to 8, intermediate source rocks ratio range from 8 to 21 and the ratio for felsic igneous rocks range from 21 to 70. In this study, the calculated Al_2O_3/TiO_2 presented in Appendix D (supplementary materials) indicates an intermediate to felsic source rocks. It is important to also note that mean values of Al_2O_3/TiO_2 (Appendix D, supplementary materials) have relatively same values with the standard published values (Appendix D, supplementary materials) of the Post Archean Australian Shale (PAAS) after Taylor and McLennan (1985) and Upper Continental Crust sediments (UCC) after Rudnick and Gao (2003), and therefore support felsic source rock signature.

The ferromagnesian trace elements such as Cr and Ni and Zr in clastic rocks are useful indicators for provenance study according to Bhatia and Crook (1986) and Condie (1993). Cullers et al. (1988), Taylor and McLennan (1985), and Wronkiewicz and Condie and Wronkiewicz (1990) concluded independently that silt fraction of sediment most closely reflects the provenance of the sediments whereby felsic source rocks usually contain lower concentrations of some trace elements like Cr, Co, Ni and V and higher concentrations of Ba, Sr, Y and Zr than mafic

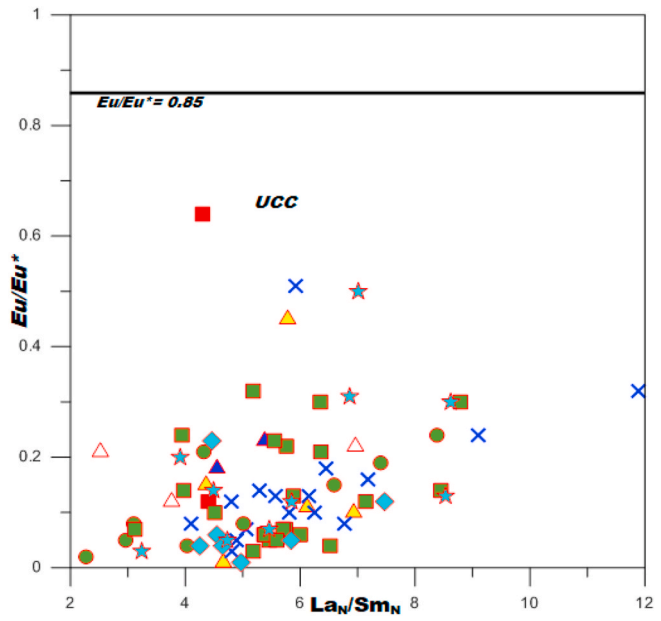


Fig. 7c. Bivariate La_N/Sm_N versus Eu/Eu* provenance variation plot showing fractionation relationship for the studied sandstone after McLennan (1989).

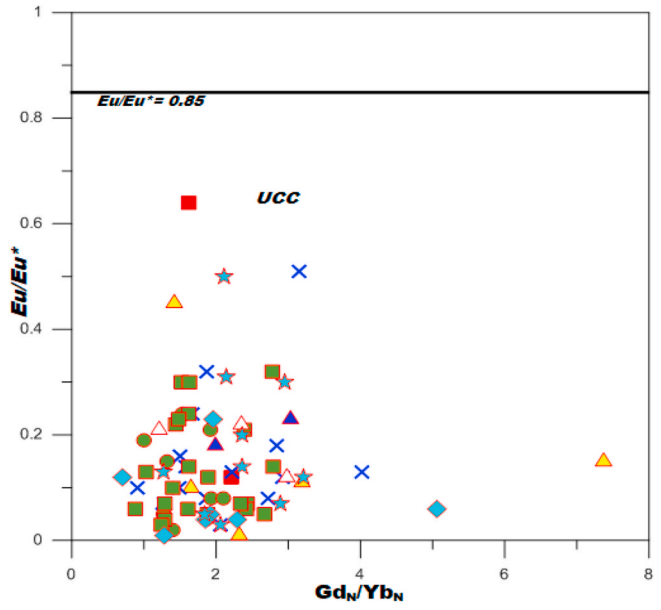


Fig. 7d. Bivariate Gd_N/Yb_N versus Eu/Eu* provenance variation plot showing fractionation relationship for the studied sandstone after McLennan (1989).

and intermediate source rocks. This is because Cr and Zr are controlled by chromite and zircon contents respectively. In this study, depletion in Ni, Co and V are observed, however, the sediments are enriched in Zr (Appendix E, supplementary materials), and thus indicate that they were principally derived from intermediate to felsic source rocks. Cullers and Podkovyrov (2000) concluded that variations in contents of Th and La are useful as indicative of the felsic source rocks while Sc and Co is an indicative of the mafic source rocks. The geochemical values of Th, La, Sc and Co of the studied sediments show similar concentrations with the published UCC and PAAS values, so, support felsic source rocks.

The ratios of immobile trace elements such as La/Th, La/Co, Th/Co, La/Sc, Th/Sc, Cr/Th, Th/Co Ba/Rb, Zr/Nb, Zr/Hf and Zr/Th are considered as good indicators of source rocks as they yield different values in felsic and basic rocks, and are considered suitable indicators of source rock provenance (Taylor and McLennan 1985; Cullers, 2002; Wronkiewicz and Condie, 1990; Rollinson, 1993; Rahman and Suzuki, 2007). The calculated mean ratio of the studied sediments (Appendix F, supplementary materials) are similar to the mean values of the UCC and PAAS data (Appendix F, supplementary materials), except for La/Co and Zr/Nb with higher relative values, thus supportive of felsic igneous source. Also, the source rock characteristics of sedimentary rocks can be determined by the uses of rare earth element (REE) concentration values, ratio and pattern (diagrams) according to Cullers et al. (1975), Bavinton and Taylor (1980), Cullers and Graf (1983), McLennan et al. (1990), Bhatia (1985), Taylor and McLennan (1985), Bhatia and Crook (1986), McLennan and Hemming (1992), and Cullers (1994). It is inferred that felsic rocks are characterized by enriched LREE and LREE/HREE ratios whereas the mafic rocks exhibit low LREE/HREE ratio (Bhatia and Crook, 1986; Wronkiewicz and Condie, 1990; McLennan and Hemming, 1992; Cullers, 1994). In this study, the REE results of the analyzed samples; the calculated sums (ΣREE), light rare earth elements (LREE), heavy rare earth elements (HREE) and ratios of the light rare earth elements to heavy rare earth elements (ΣLREE/ΣHREE) presented in Appendix H (supplementary materials) show LREE enrichment than HREE, therefore, indicate felsic igneous rock origin. It is also interesting to note that the mean values of LREE/HREE for the studied sediments are similar to PAAS and UCC (Appendix H, supplementary materials) which support sediment derivation from felsic source.

By employing the elements-based provenance discriminant plots, e.g. bivariate Al_2O_3/TiO_2 versus SiO_2(%) plot (Fig. 6a) after Le Bas et al. (1986), TiO_2(%) versus Zr (ppm) plot (Fig. 6b) after Hayashi et al. (1997), TiO_2(%) versus Ni(ppm) plot (Fig. 6c) after Floyd et al. (1989), Cr/V versus Y/Ni plot (Fig. 6d) after Floyd et al. (1990) and Hayashi et al. (1997), Th/Sc versus Sc plot (Fig. 6e) after McLennan et al. (1983), Th/Co versus La/Sc plot (Fig. 6f) after Mclennan et al. (1980), Mclennan and Taylor (1991) and Cullers (2002), La/Th versus Hf plot (Fig. 6g) after Floyd et al. (1990) and Hayashi et al. (1997) with ternary plots of SiO_2/10-CaO+MgO-Na_2O+K_2O (Fig. 6h) after Taylor and McLennan (1985), La-Th-Sc (Fig. 6i) after Roser and Korsch (1986) and V-Ni-Th*10 (Fig. 6j) after Bracciali et al. (2007) confirmed that the sediments within the northern Bida Basin were sourced from an acidic igneous felsic provenance field.

Generally, the REE pattern and Europium anomaly (Eu/Eu*) in the sedimentary rocks provide clues for the source rock characteristics (Cullers and Graf, 1983; Dickinson, 1985; Taylor and McLennan, 1985; McLennan et al., 1990; Cullers, 1994, 1995) because felsic rocks are characterized by negative Eu/Eu* (<1.0) whereas the mafic rocks exhibit positive but low Eu/Eu* (>1.0). In this study, the obtained Eu/Eu* values (Appendix H, supplementary materials) are generally less than 1.0 which is indicative of negative Eu/Eu*, therefore a felsic source derivation is suggested. The studied sandstones also display very low values of Eu/Eu* compared with UCC (0.66) and PAAS (0.71), and it therefore supports the felsic origin. The degree of light REE (LREE) versus heavy REE (HREE) enrichment can also be assessed through the ratio of chondrite-normalized La and Yb values (La_N/Yb_N). In this study, the fractionation within the LREE and the HREE revealed significant LREE enrichment with nearly flat chondrite-normalized HREE patterns of La_N/Yb_N for the studied sediments (Fig. 7a–d). Also, according to McLennan (1989) and Mclennan and Taylor (1991), the ratio of normalized Gd to Yb (Gd_N/Yb_N) can be employed to document the nature and composition of source rocks in the sedimentary rocks. They stated that UCC sediment generally have higher value of Gd_N/Yb_N ratios typically above 2.0, whereas the PAAS value commonly ranges between 1.0 and 2.0. In this study, the calculated mean values of Gd_N/Yb_N (Appendix H, supplementary materials) generally fall and fit within the UCC and PAAS sediment classification values. Also, like Gd_N/Yb_N ratios, Sm/Nd ratios show low mean values which is line with the felsic protolith revealed from other geochemical proxies above.

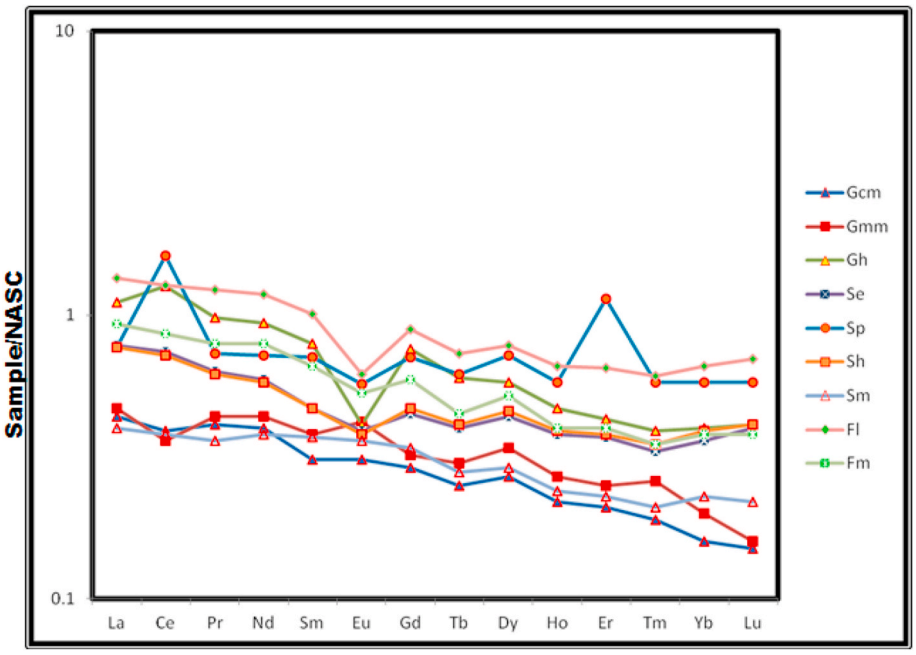


Fig. 8a. Spider plot of rare earth element (REE) of studied sandstone, normalized against average upper continent values (UCC) after McLennan (1989).

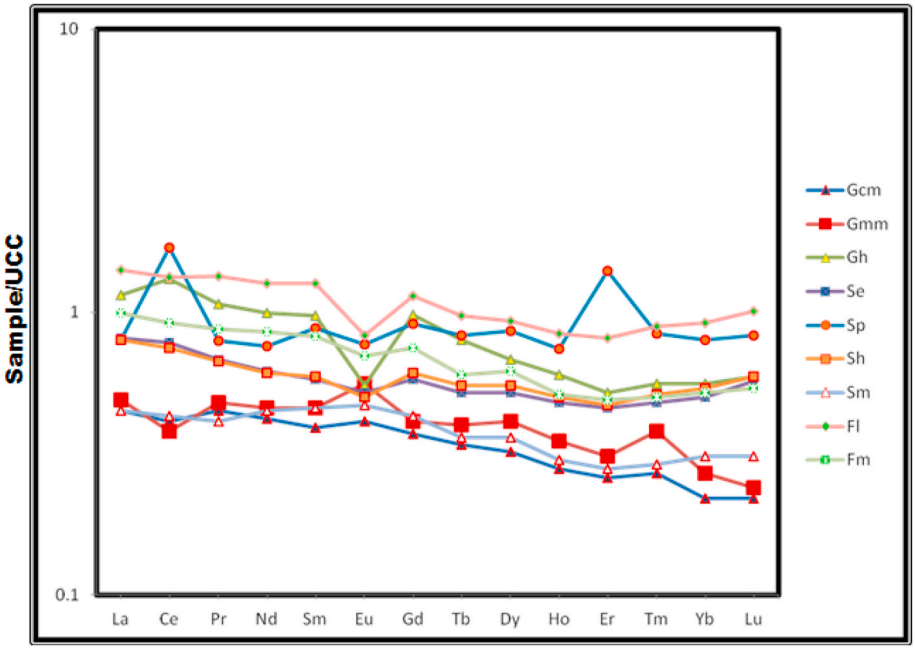


Fig. 8b. Spider plot of rare earth element (REE) of studied sandstone, normalized against average North American Shale Composite (NASC) after Gromet et al. (1984).

Normalization of REE in rocks is important as it functions to eliminates variation between odd and even atomic number element and it may allow fractionation of the REE group relative to chondrite meteorites to be identified (Rollinson, 1993; McLennan, 1989). The patterns also help distinguish felsic from mafic source of clastic sedimentary rocks (McLennan, 1989). The concentrations of the rare earth elements of the studied samples have been normalized with the concentrations of the Chondrite after Boynton (1984), Upper Continental Crust (UCC) after Taylor and McLennan (1985), North Archean Australian Shale after Gromet et al. (1984) and Post Archean Australian Average Shale (PAAS) after Taylor and McLennan (1985). In this study, the Chondrite normalized plots of the UCC (Fig. 8a), the NASC (Fig. 8b) and the PAAS (Fig. 8c) show a relatively flattened HREE patterns and relatively steep depletion of LREE which also indicates a substantial contribution from felsic provenance.

4.6. Paleotectonic settings

The mineralogical and geochemical compositions of clastic sedimentary rocks have been employed in several related studies in the past (Condie et al., 2001) as they provide an insight to their provenance and tectonic settings. Accordingly, it is possible to reconstruct the paleotectonic settings of source areas by analyzing the detrital modes of siliciclastic strata in diverse depositional basins (Ingersoll et al., 1995).

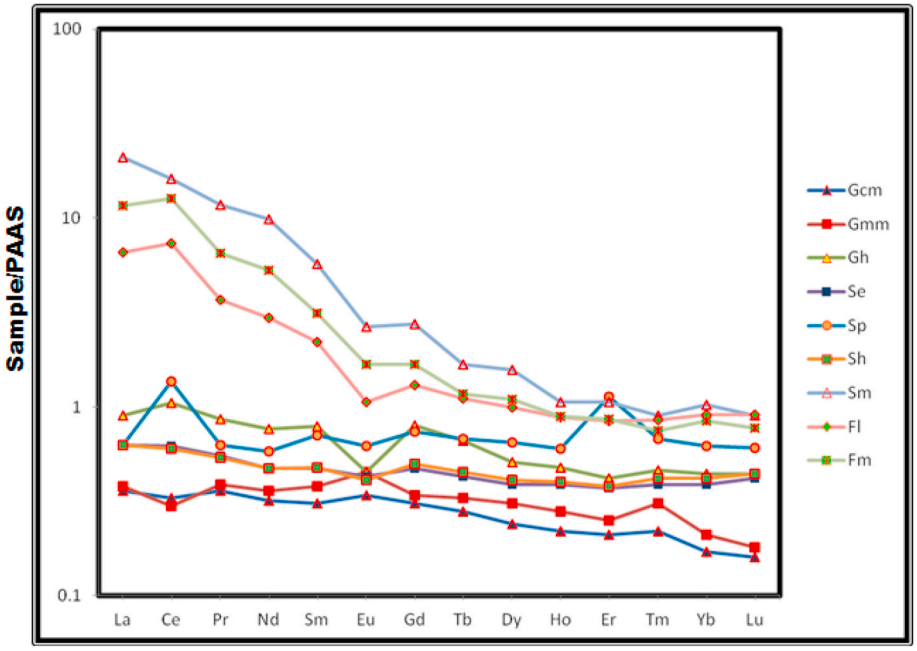


Fig. 8c. Spider plot of rare earth element (REE) of studied sandstone, normalized against average Post Archean Australian Shale (PAAS) values after McLennan (2001).

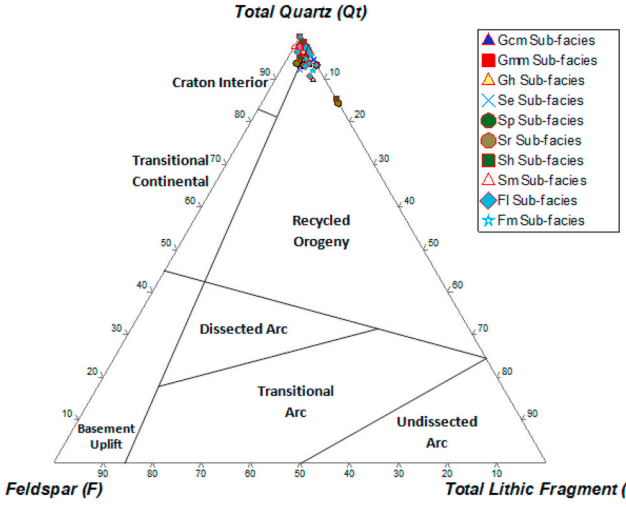


Fig. 9a. Standard Qt-F-Lt Provenance Ternary plot after Dickinson (1985) showing Craton Interior and Recycled Orogeny fields for the studied sandstone.

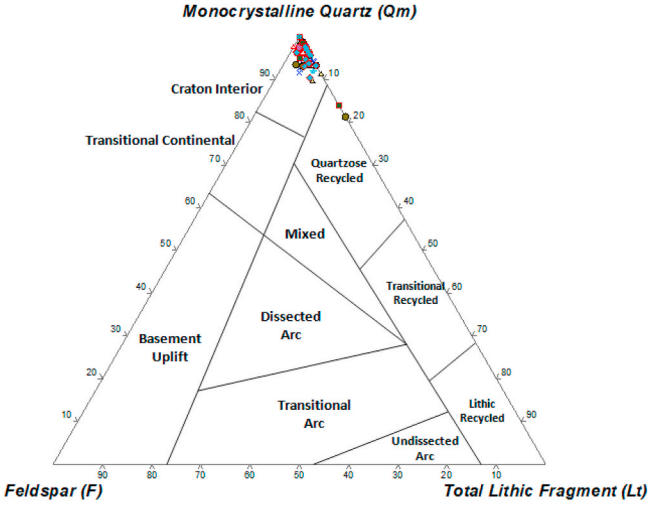


Fig. 9b. Standard Qm-F-Lt Provenance Ternary plot after Dickinson et al. (1983) showing Craton Interior and Recycled Orogeny field for the studied sandstone.

Thus, sandstone petrofacies analysis can furnish vital clues regarding the provenance and its tectonic setup and source rock composition. The ternary plots after Dickinson and Suczek (1979) and Dickinson et al. (1983) use the modal framework compositions and were employed in this study for tectonic settings discrimination of the Bida Basin. Crook (1974) proposed the use of quartz contents to infer paleotectonic setting, and linked quartz rich (>65% quartz) sandstones to passive continental margins (Atlantic type); intermediate quartz (15–65% quartz) sandstones to active continental margins (Andean type), and quartz poor (<15% quartz) sandstones to magmatic island arcs. Evidence of quartz rich (>65% quartz) in the studied sediments thus correspond to passive continental margins sandstones.

Applications of ternary discrimination diagram using modal framework compositions plots in this study; Qt-F-Lt diagram after Dickinson and Suczek (1979), Qm-F-Lt diagram after Dickinson (1985) and Qt-F-L diagram after Dickinson et al. (1983) shows that all the studied sediments plotted within the craton interior and minor recycled orogeny provenance representing material from a continental block provenance (Fig. 8a–c). This presumably indicates possible mixing of sediment from an eroded, mature continental island arc, passive margin and from quartzose recycled sources. Therefore, the source rocks may be of two types: a continental source (responsible for the quartz fragments and the high resistant lithic grains) and a plutonic-arc source (responsible for the amounts of quartz, feldspar and plutonic accessory-mineral fragments). The near absence or negligible proportion of polycrystalline quartz grains and metamorphic lithic fragments in Appendix B (Supplementary materials) suggests that the source region may have been uplifted in an extensional or transform setting as suggested by Dickinson (1985).

Geochemical approaches to provenance and paleotectonic settings study are important, not only to support but also to identify features not readily recognized by petrography. Several past studies including Bhatia

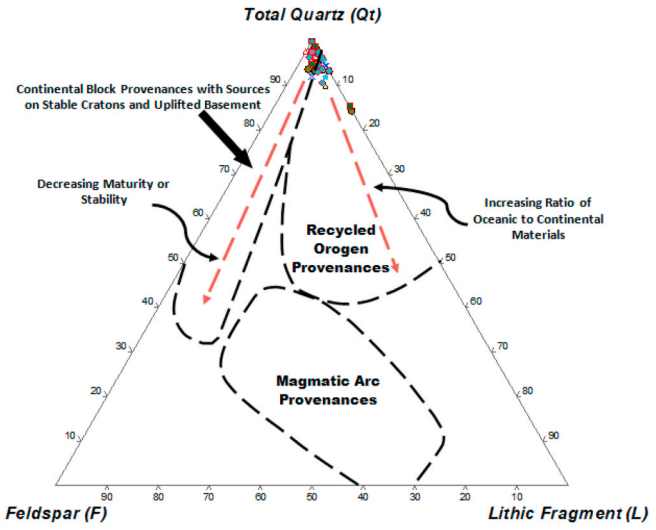


Fig. 9c. Standard Qm-F-Lt Provenance Ternary plot after Dickinson et al. (1982) showing Continental Block Provenances filed for the studied sandstone.

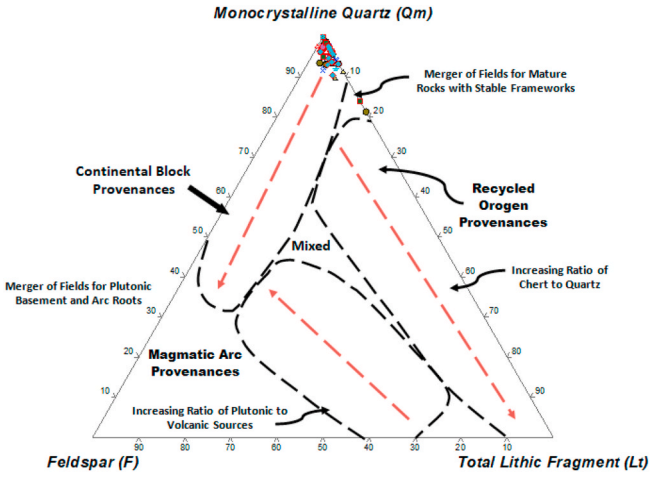


Fig. 9d. Standard Qt-F-L Provenance Ternary plot after Dickinson et al. (1983) showing Continental Block Provenances filed for the studied sandstone.

and Crook (1986), Roser and Korsch (1986, 1988) have shown that chemical compositions of siliciclastic sedimentary rocks are significantly controlled by tectonic settings of their provenances and depositional basins, and as a result, the rocks from different tectonic settings possess terrain-specific geochemical signatures. The tectonics discrimination diagrams proposed by Bhatia (1983), Bhatia and Crook (1986), and Roser and Korsch (1986) and widely used in sedimentary geochemical studies to identify the tectonic settings of unknown basins is also employed in this paper. Major oxides especially those with relative abundance of immobile oxides (SiO_2 and TiO_2) and depletion of the mobile phases (Al_2O_3, K_2O, CaO and Na_2O) and their ratios; Al_2O_3/SiO_2, K_2O/Na_2O, and $Al_2O_3/(CaO+Na_2O)$ are very useful geochemical tools for paleotectonic settings deduction of clastic sedimentary rocks according to Crook (1974), Bhatia (1983), Roser and Korsch (1986) and McLennan et al. (1990). The authors demonstrated that SiO_2 contents and K_2O/Na_2O ratios of sandstone appear to be particularly sensitive indicators of geotectonic setting, so, they suggested that the quartz-poor greywackes (quartz<15%, mean SiO_2-58%, $K_2O/Na_2O < 1$) are indicative of magmatic island arcs which is an approximate average composition of the tholeiitic andesite, the quartz intermediate greywackes (quartz = 15–65%, mean SiO_2-68-74%, $K_2O/Na_2O < 1$) are indicative of Andean-type continental margins and have approximately

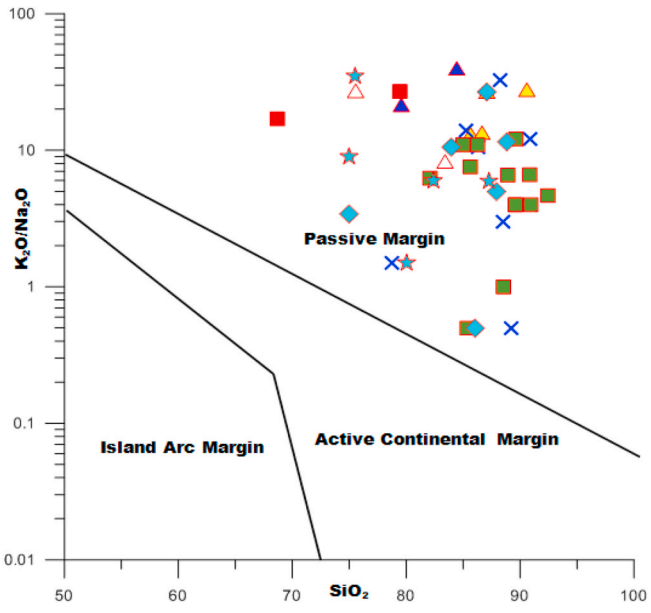


Fig. 10a. Bivariate log(K_2O/Na_2O) versus SiO_2 paleotectonic discrimination plot after Roser and Korsch (1986) showing Passive Margin paleotectonic settings for the studied sandstone.

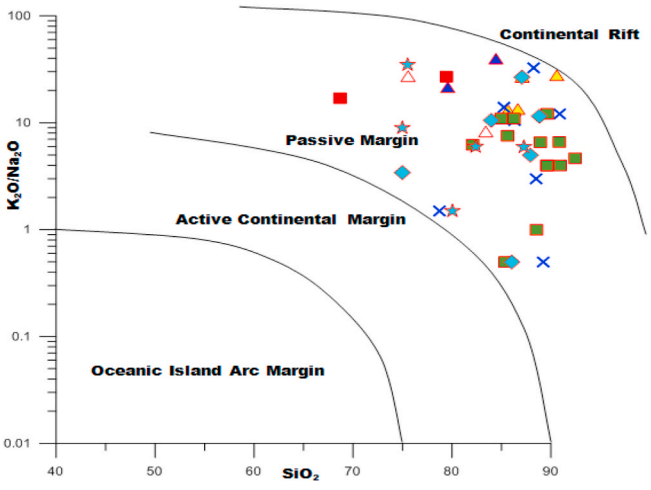


Fig. 10b. Bivariate log(K_2O/Na_2O) versus SiO_2 paleotectonic discrimination plot after Murphy (2000) showing Passive Margin paleotectonic settings for the studied sandstone.

the same composition as the upper level of continental crust while quartz-rich greywackes (quartz>65%, mean SiO_2 = 89%, $K_2O/Na_2O >$ 1) are characteristic of Atlantic-type continental margins and are similar in composition to the sand fraction of the continental platform cover. The parameters obtained from this study (Appendix B, supplementary materials) fall in the quartz-rich greywackes class indicating Atlantic-type continental margins.

Dickinson and Suczek (1979) and Bhatia (1983) suggested a progressive decrease in Fe_2O_3+MgO, TiO_2, Al_2O_3/SiO_2 and an increase in K_2O/Na_2O and $Al_2O_3/(CaO+Na_2O)$ trends in major elemental geochemical compositions of clastic suites that implies maturity in different tectonic settings; oceanic island arc, continental island arc, active continental margins and passive margins. They concluded that sandstones of sedimentary basins adjacent to oceanic island arcs are characterized by high abundances of Fe_2O_3+MgO (8–14%) with TiO_2 (0.8–1.4%) and high mean ratios of Al_2O_3/SiO_2 (0.24–0.33) with lower

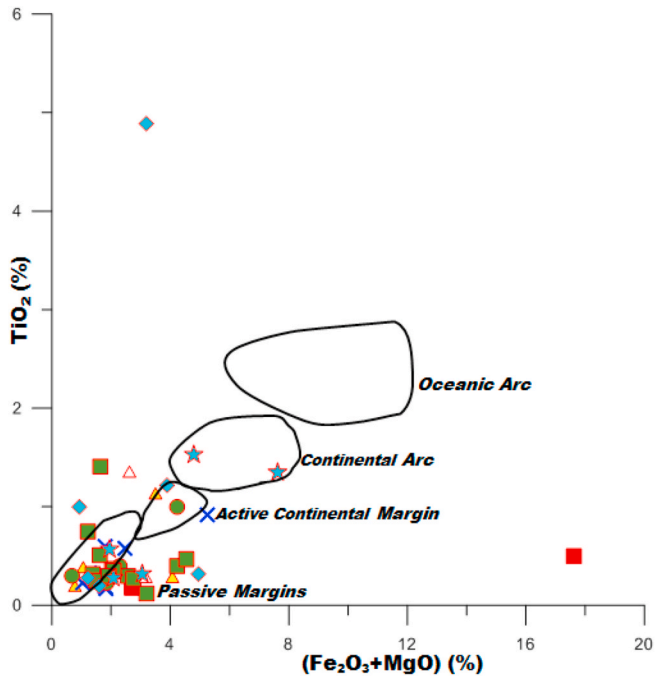


Fig. 10c. Bivariate TiO_2 versus (Fe_2O_3+MgO) paleotectonic discrimination plot after Bhatia (1983) showing Passive Margin paleotectonic settings for the studied sandstone.

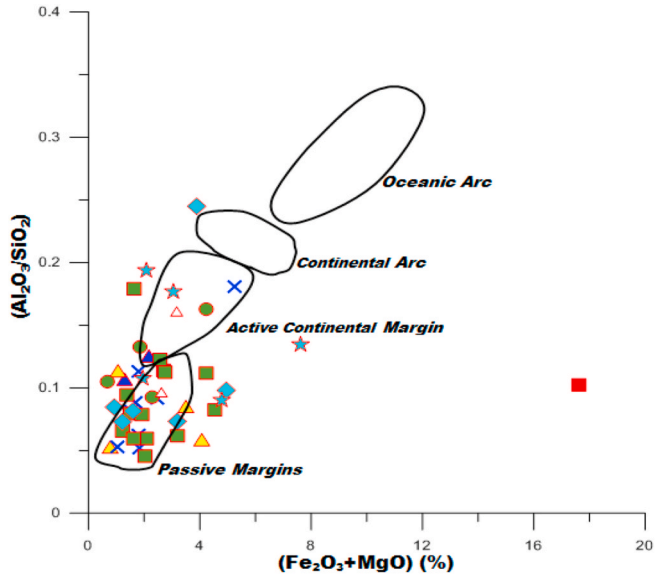


Fig. 10d. Bivariate (Al_2O_3/SiO_2) versus (Fe_2O_3+MgO) paleotectonic discrimination plot after Bhatia (1983) showing Passive Margin paleotectonic settings for the studied sandstone.

K_2O/Na_2O (0.2–0.4) ratio. Also, sandstones of basins adjacent to continental island arcs from oceanic island-arc types have lower Fe_2O_3+MgO (5–8%), TiO_2 (0.5–0.75) with Al_2O_3/SiO_2 (0.15–0.22) and higher K_2O/Na_2O (0.4–0.8) ratios while sandstones from active continental margins basins have very low Fe_2O_3+MgO (2–5%) and TiO_2 (0.25–0.45%) with K_2O/Na_2O ratio of approximately 1. We compare the values (Appendices C and D, supplementary materials) obtained from these parameters in our study with the above geochemical standards, and observed that our samples fit more into passive margin fields (as it is generally enriched in SiO_2 and depleted in Al_2O_3, TiO_2, Na_2O, CaO with K_2O/Na_2O ratio greater than 1).

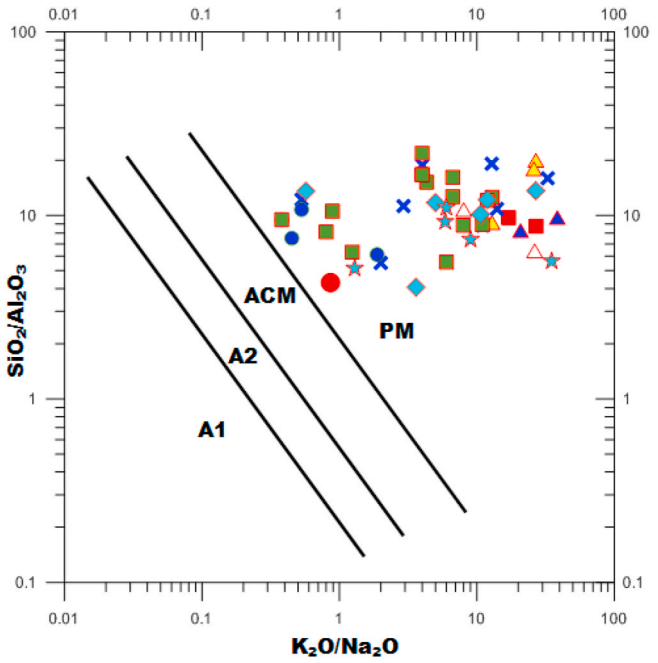


Fig. 10e. Bivariate SiO_2/Al_2O_3 versus K_2O/Na_2O paleotectonic discrimination plot after Roser and Korsch (1988) showing Passive Margin paleotectonic settings for the studied sandstone. NB: A1 – Arc setting, basaltic and andesitic detritus; A2 – Evolved arc setting, Felsic-Plutonic detritus; ACM - Active Continental Margin; PM - Passive Margin.

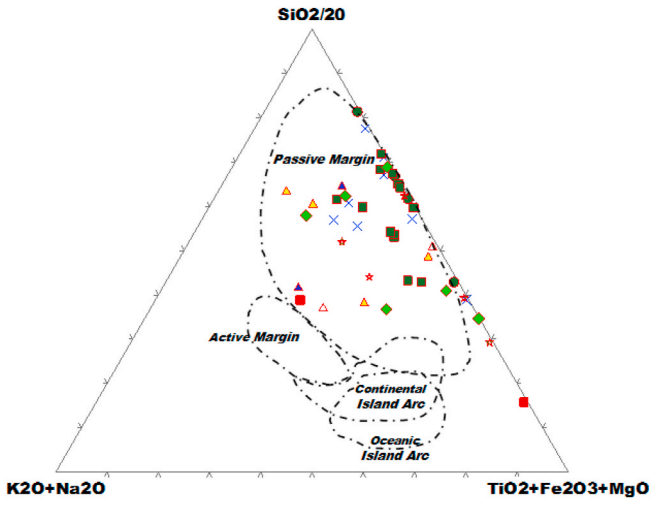


Fig. 10f. The standard paleotectonic discrimination ternary plot of $SiO_2/20$-(K_2O+Na_2O)-(TiO_2+Fe_2O_3+MgO) after Kroonenberg (1994) showing Passive Margin field for the studied sandstone.

The discrimination diagram of log(K_2O/Na_2O) versus SiO_2 after Roser and Korsch (1986) defined three main tectonic provenance on the basis of chemical composition of sandstones as follows; passive continental margin (PM) that composed of mineralogically mature (quartz--rich) sediments deposited in plate interiors at stable continental margins or intracratonic basins (mainly sourced from recycled sedimentary and metamorphic source rocks), active continental margin (ACM) with sediments composed of intermediate quartz content derived from tectonically active continental margins and deposited on or adjacent to active plate boundaries (e.g. trench, forearc and backarc settings) (mainly sourced from granites, gneisses, siliceous volcanic) and oceanic island arc (OIA) composed of quartz poor volcanogenic sediments

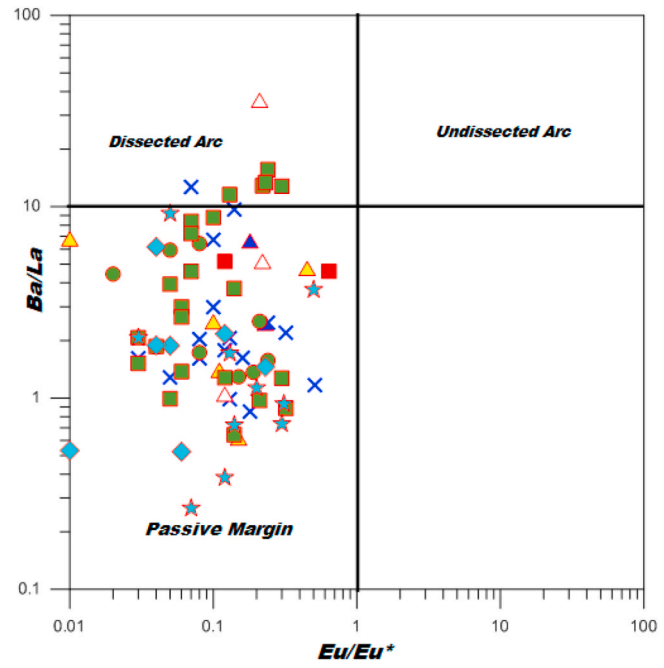


Fig. 10g. Bivariate discrimination plot of Ba/La versus Eu/Eu* after Bhatia (1985) showing passive margin field for the studied sandstones.

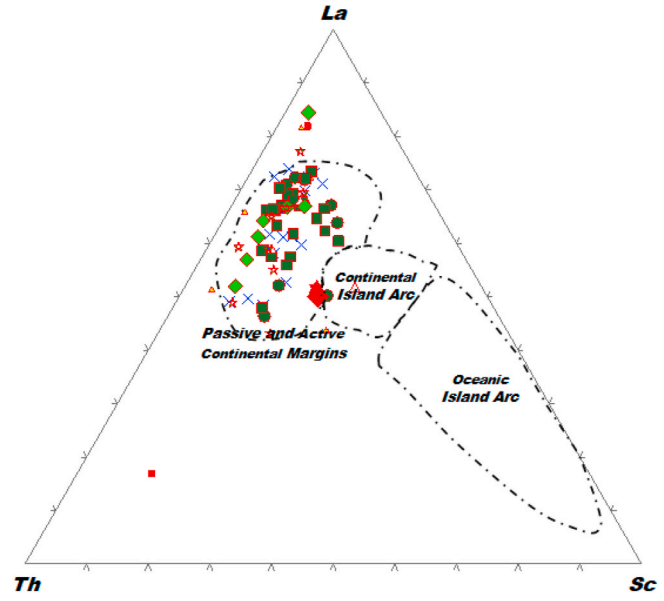


Fig. 10h. The standard La-Th-Sc Ternary Tectonic discrimination diagram after Bhatia and Crook (1986) showing Passive Continental Margin fields for the studied sandstones.

derived from oceanic island arcs and deposited in a variety of settings including forearc, intra-arc and backarc basins etc (mainly sourced from calcalkaline or tholeiitic rocks). The plots presented in Fig. 9a–d show quartz-rich sediments (mineralogically mature) and therefore, support passive continental margin (PM) in the study area (see Fig. 10).

Several classifications have been attempted by previous workers (e.g. Maynard et al., 1982; Bhatia, 1983; Bhatia and Crook, 1986; Roser and Korsch, 1986, 1988) to discriminate various origins and tectonic settings. The tectonic setting geochemical discriminant plots in sandstone suites includes; bivariate and ternary plots of $\log(K_2O/Na_2O)$ versus SiO_2 after Roser and Korsch (1986) and Murphy (2000), the TiO_2 versus

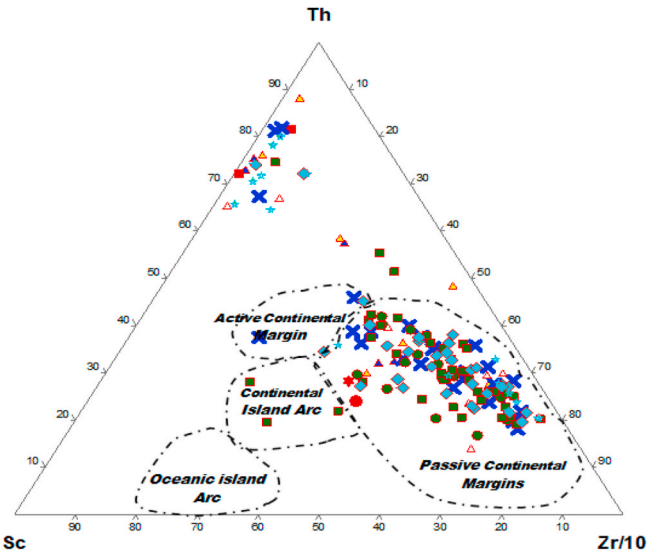


Fig. 10i. The standard Th-Sc-Zr/10 Ternary Tectonic discrimination diagram after Bhatia and Crook (1986) showing Passive Continental Margin as the setting for the studied sandstones.

(Fe_2O_3+MgO), Al_2O_3/SiO_2 versus (Fe_2O_3+MgO), SiO_2/Al_2O_3 versus K_2O/Na_2O after Roser and Korsch (1988), SiO_2/20-(-K_2O+Na_2O)-(TiO_2+Fe_2O_3+MgO) after Kroonenberg (1994) are very useful in separating data into broad tectonic discrimination groups; passive margin (PM), oceanic island arc (OIA), continental island arc (CIA), active continental margin (ACM) and passive margin (PM) because they are sensitive indicators of paleotectonic settings of the sediments' provenance. In this study, the same patterns of paleotectonic field were observed in all the discrimination plots as all the studied sediments plotted within and near passive margin field (Fig. 10a–f).

Trace elements are more useful for discriminating tectonic settings of siliclastics as compared to major elements because of concentration in accessory phases that may be subjected to hydraulic concentration (Bhatia and Crook, 1986). The abundance and plots of chromium (Cr), nickel (Ni), rubidium (Rb), Niobium (Nb), Thallium (Ta), vanadium (V), scandium (Sc), lanthanum (La), barium (Ba) in siliciclastic sediments could be useful in separating the provenance because each field (passive margin, continental recycled, dissected arc and undissected arcs) are well separated and plotted in definable groups. Bhatia (1985), Bhatia and Crook (1986) has showed than there is an increase in REE abundance, with a high values of LREE to HREE ratios and a decrease in the Eu anomaly as the sandstones became more mature. They independently suggested that the sediments deposited in the continental margin are enriched in ΣREE and LREE with negative Europium anomaly (Eu/Eu*), whereas sediments deposited in an oceanic arcs are depleted in ΣREE and LREE and lack negative Eu/Eu*. Bhatia (1985) and McLennan (1989) also stated that passive margin provenance is typically characterized with uniform REE pattern similar to PAAS, whereas sediments from active continental margin display intermediate ΣREE abundances with variable negative Eu/Eu* in the range of 0.6–1.0. In this study, the mean Eu/Eu* values (Appendix H, supplementary materials) of all the study sediments suggest the sediments are deposited within the passive margin setting.

The clear explanation of the passive margin tectonic settings is such that it comprises rifted continental margins; sedimentary basins on trailing continental margins supplied from collision orogeny and inactive or extinct convergent plate margins. The Ba/La versus Eu/Eu* is a plot that shows the relationships between the Ba/La ratio and Eu anomaly derived from the normalization of Chondrite values with the study sediments. Bhatia (1985) suggested that Arc rocks should typically have ratios of Ba/La and Eu/Eu* that are greater than 1 while passive

margin sediments usually have Ba/La ratios less than 1 and Eu/Eu* less than or equal to one (1.0). The plot of Ba/La versus Eu/Eu* presented in Fig. 10g identified sediments source from passive margin sediments group. The plot also showed a distinct negative Eu anomaly and low Ba/La ratios. The application of the discriminant bivariate and ternary plots; Lanthanum-Thorium-Scandium (La-Th-Sc) after McLennan et al. (1983) and Thorium-Scandium-Zirconium/10 (Th-Sc-Zr/10) after Bhatia and Crook (1986) also confirm that all the studied sediments were plotted and clusters within the passive continental margin field (Fig. 10h and i).

5. Conclusions

The present study shows predominance of angular to sub-angular detrital grains with variations in quartz abundance among the detrital framework with higher monocrystalline/polycrystalline ratios. Petrofacies and geochemical data indicate quartzarenite to sublitharenite petrofacies. The sandstones were derived from a felsic source rocks in a tectonically stable passive continental margin within craton interior/continental block to recycled orogeny provenance.

We conclude that combined petrographic and geochemical data strongly suggest that the siliciclastic sediments in the Northern Bida Basin were derived from plate interiors or stable continental areas and deposited in a stable intra-cratonic basin.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafrearsci.2020.104041.

References

Adeleye, D.R., Dessauvagie, T.F.J., 1972. In: Dessauvagie, T.F.J., Whiteman, A.J. (Eds.), Stratigraphy of the Niger Embayment, Near Bida, Nigeria, African Geology. University of Ibadan Press, Ibadan, pp. 181–185.
Adeleye, D.R., 1972. Cretaceous sediments from the shores of lake Kainji, Nigeria. J. Min. Geol. 7, 5–12.
Adeleye, D.R., 1973. Origin of ironstones, an example from the Middle Niger basin, Nigeria. J. Sediment. Petrol. 43 (3), 709–727.
Adeleye, D.R., 1974. Sedimentology of the fluvial Bida sandstones (cretaceous), Nigeria. Sediment. Geol. 112, 1–24.
Adepoju A., S., 2019. Sedimentary geology and geochemical studies of the upper Cretaceous sandstones, northern Bida Basin. University of Ilorin, pp. 1–523.
Agyingi, C.M., 1993. Palynological evidence for a late cretaceous age for Patti Formation, eastern Bida basin, Nigeria. J. Afr. Earth Sci. 17, 513–523.
Basu, A., 1976. Petrology of Holocene fluvial sand derived from plutonic source rocks: implications to paleoclimate interpretation. J. Sediment. Petrol. 46, 694–709.
Basu, A., 1985. Reading provenance from detrital quartz. In: Zuffa, G.G. (Ed.), Provenance of Arenites: Dordrecht, NATO-ASI. Reidel, pp. 231–248.
Basu, A., Young, S.W., Suttner, L.J., 1975. Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation. J. Sediment. Petrol. 4, 873–882.
Bavinton, O.A., Taylor, S.R., 1980. Rare earth element abundances in Archean metasediments from Kambalda, Western Australia. Geochem. Cosmochim. Acta 44, 639–648.
Bhatia, M.R., Crook, K.A.W., 1986. Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. Contrib. Mineral. Petrol. 92, 181–193.
Bhatia, M.R., 1983. Plate tectonics and geochemical composition of sandstones. J. Geol. 91, 611–627.
Bhatia, M.R., 1985. Rare earth element geochemistry of Australian Paleozoic graywackes and mudrocks: provenance and tectonic control. Sediment. Geol. 45, 97–113.
Blatt, H., Middleton, G., Murray, R., 1980. Origin of Sedimentary Rocks. Prentice-Hall Inc., Englewood Cliffs, p. 782p.
Boynton V., W., 1984. Cosmochemistry of the rare earth elements: meteorite studies. In: Henderson, P. (Ed.) Rare Earth Element Geochemistry. Elsevier Science, pp. 63–114.
Bracciali, L., Marroni, M., Pandolfi, L., Rocchi, S., 2007. Geochemistry and petrography of Western Tethys Cretaceous sedimentary covers (Corsica and Northern Apenninces): from source areas to configuration of margins. In: Arribas, J., Critelli, S., Johnsson, M.J. (Eds.), Sedimentary Provenance and Petrogenesis: Perspectives from Petrography and Geochemistry, vol. 420. Geological Society of America Special Paper, pp. 73–93.
Braide P, S., 1992. Syntectonic fluvial sedimentation in the central Bida Basin. Journal of Mining and Geology 28, 55–64.
Carozzi, A.V., 1993. Sedimentary Petrography. PTR Prentice Hall, Englewood Cliffs, New Jersey, p. 263.
Condie, K.C., Wronkiewicz, D.J., 1990. A new look at the Archean-Proterozoic boundary: sediments and the tectonic setting constraint. In: Naqvi, S.M. (Ed.), Precambrian Continental Crust and its Economic Resources. Elsevier, Amsterdam, pp. 61–84.
Condie, K.C., 1993. Chemical composition and evolution of the upper continental crust: contrasting results from surface samples and shales. Chem. Geol. 104, 1–37.
Condie, K.C., Boryta, M.D., Liu, J., Quian, X., 1992. The origin of khondalites: geochemical evidence from the Archean to Early Proterozoic granulitic belt in the North China Craton. Precambrian Res. 59 (3–4), 207–223.
Condie, K.C., Lee, D., Farmer, L., 2001. Tectonic setting and provenance of the Neoproterozoic Uinta Mountain and Big Cootonwood groups, northern Utah: constraints from geochemistry, Nd isotopes, and detrital modes. Sediment. Geol. 141–142, 443–464.
Critelli, S., Ingersoll, R.V., 1995. Interpretation of neovolcanic versus paleovolcanic sand grains: an example from Miocene deep marine sandstones of the Topanga Group (Southern California). Sedimentology 42, 783–804.
Crook, K.A.W., 1974. Lithogenesis and geotectonics: the significance of compositional variation in flysch arenites (graywackes). In: Dott (Ed.). In: H Jr., R., Shaver, R.H. (Eds.), Modern and Ancient Geosynclinal Sedimentation, vol. 19. SEPM Special Publication, pp. 304–310.
Cullers, R.L., Graf, J., 1983. Rare earth elements in igneous rocks of the continental crust: intermediate and silicic rocks, or petrogenesis. Rare-Earth Geochemistry. Elsevier, Amsterdam, pp. 275–312.
Cullers, R.L., Podkovyrov, V.N., 2000. Geochemistry of the Mesoproterozoic Lakhanda shales in southeastern Yakutia, Russia: implications for mineralogical and provenance control, and recycling. Precambrian Res. 104, 77–93.
Cullers, R.L., 1994. The chemical signature of source rocks in size fractions of Holocene stream sediment derived from metamorphic rocks in the wet mountains region, Colorado, USA. Chem. Geol. 113, 327–343.
Cullers, R.L., 2002. Implications of elemental concentrations for provenance, redox conditions and metamorphic studies of shales and limestones near Pueblo, Co, USA. Chem. Geol. 191 (4), 305–327.
Cullers, R.L., Basu, A., Suttner, L.J., 1988. Geochemical signature of provenance in sand-size material in soils and stream sediments near the Tobacco Root batholith, Montana, USA. Chem. Geol. 70, 335–348.
Cullers, R.L., Chaudhuri, S., Arnold, B., Lee, M., Wolf, C.W., 1975. Rare earth distributions in clay minerals and in clay-sized fraction of the lower Permian Havensville and Eskridge shales of Kansas and Oklahoma. Geochem. Cosmochim. Acta 39, 1691–1703.
Datta, B., 2005. Provenance, tectonics and palaeoclimate of Proterozoic Chandarpur sandstones, Chattisgarh basin: a petrographic view. J. Earth Syst. Sci. 114, 227–244.
Dickinson, W.R., Rich, E.I., 1972. Petrologic intervals and petrofacies in the Great valley sequence, sacramento valley, California. Geol. Soc. Am. Bull. 83, 3007–3024.
Dickinson, W.R., Suczek, C.A., 1979. Plate tectonics and sandstone compositions. AAPG (Am. Assoc. Pet. Geol.) Bull. 63, 2164–2182.
Dickinson, W.R., 1970. Interpreting detrital modes of greywacke and arkose. J. Sediment. Petrol. 40, 695–707.
Dickinson, W.R., 1985. Interpreting provenance relations from detrital modes of sandstones. In: Zuffa, G.G. (Ed.), Provenance of Arenites. NATO-ASI Series, 148. Reidel Publishing Company, Dordrecht, pp. 333–361.
Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Evjavec, J.L., Ferguson, R.C., Inman, K. F., Knepp, R.A., Lindberg, F.A., Ryberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geol. Soc. Am. Bull. 94, 222–234.
Dickinson, W.R., Ingersoll, R.V., Cowan, D.S., Helmold, K.P., Suczek, C.A., 1982. Provenance of Franciscan graywackes in coastal California. Geol. Soc. Am. Bull. 93, 95–107.
Dorsey, R.J., 1988. Provenance evolution and unroofing history of a modern arc-continent collision: evidence from petrography of Plio-Pleistocene sandstones, eastern Taiwan. J. Sediment. Petrol. 58, 208–218.
Falconer, J.D., 1911. The Geology and Geography of Northern Nigeria. Macmillan, London, p. 135.
Floyd, P.A., Franke, W., Shail, R., Dörr, W., 1990. Provenance and depositional environment of Rhenohercynian synorgenic greywacke from the Giessen nappe, Germany. Geol. Rundsch. 79, 611–625.

Floyd, P.A., Winchester, J.A., Park, R.G., 1989. Geochemistry and tectonic setting of Lewisian clastic metasediments from the early proterozoic Loch maree group of Gairloch, NW scotland. Precambrian Res. 45, 203–214.
Folk, L., 1980. Petrology of Sedimentary Rocks. Austin Texas, Hemphill, p. 182p.
Gazzi, P., 1966. Le arenarie del fl ysch sopracretaceo dell'Appennino modensese: correlazioni con il flysch di Monghidoro. Mineral. Petrogr. Acta 12, 69–97.
Gromet, L.P., Dymek, R.F., Haskin, L.A., Korotev, R.L., 1984. The North American Shale Composite: its compilation, major and trace element characteristics. Geochem. Cosmochim. Acta 48, 2469–2482.
Hayashi, K., Fujisawa, H., Holland, H., Ohmoto, H., 1997. Geochemistry of 1.9 Ga sedimentary rocks from northeastern Labrador, Canada. Geochem. Cosmochim. Acta 61 (19), 4115–4137.
Herron, M.M., 1988. Geochemical classifications of terrigenous sands and shales from core or log data. J. Sediment. Petrol. 58, 820–829.
Ingersoll, R.V., Bulard, T.F., Ford, R.L., Grimn, J.P., Pickle, J.P., Sares, S.W., 1984. The effect of grain size on detrital modes: a text of the Gazzi-Dickinson Point Counting method. J. Sediment. Petrol. 54, 103–115.
Ingersoll, R.V., Graham, S.A., Dickinson, W.R., 1995. Remnant ocean basins. In: Busby, C.J., Ingersoll, R.V. (Eds.), Tectonics of Sedimentary Basins. Blackwell, Oxford, pp. 363–391.
Jan du Chene, J., Adegoke, O.S., Adediran, S.A., Petters, S.W., 1978. Palynology and foraminifera of the Lokoja sandstone (Maastrichtian), Bida basin Nigeria. Rev. Espanola Micropaleontol. 10 (3), 379–393.
Johnsson, M.J., 1993. The system controlling the composition of clastic sediments. In: Johnsson, M.J., Basu, A. (Eds.), Processes Controlling the Composition of Clastic Sediments, vol. 284. Geological Society of America, Special Paper, pp. 1–19.
Kennedy, W.Q., 1965. The influence of basement structure on the evolution of the coastal (Mesozoic and Tertiary) basins. In: Recent Basins Around Africa, Proceedings of the Institute of Petroleum Geologists Society, pp. 35–47. London.
King, L.C., 1950. Outline and distribution of Gondwanaland. Geol. Mag. 87, 353–359.
Kogbe, C.A., Ajakaiye, D.E., Matheis, G., 1983. Confirmation of rift structure along the Mid-Niger valley, Nigeria. J. Afr. Earth Sci. 1, 127–131.
Kroonenberg, S.B., 1994. Effects of Provenance, sorting and weathering on the geochemistry of fluvial sands from different tectonic and climatic environment. Proc. 29th Int. Geol. Congr., Part A 69–81.
Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. J. Petrol. 27, 745–750.
Maynard, J.B., Valloni, R., Yu, H., 1982. Composition of modern deep-sea sands from arc-related basins, 10. Geological Society of London, Special Publication, pp. 551–561, 1.
McBride, E.F., 1963. A classification of common sandstones. J. Sediment. Petrol. 33, 664–669.
McLennan, S.M., Hemming, S., 1992. Sm/Nd elemental and isotopic systematics in sedimentary rocks. Geochem. Cosmochim. Acta 56, 887–898.
Mclennan, S.M., Taylor, S.R., 1991. Sedimentary rocks and crustal evolution: tectonic setting and secular trends. J. Geol. 99, 1–21.
McLennan, S.M., 1989. Rare earth elements in sedimentary rocks; influence of provenance and sedimentary processes. In: Lipin, B.R., McKay, G.A. (Eds.), Geochemistry and Mineralogy of Rare Earth Elements, Reviews in Mineralogy, vol. 21, pp. 169–200.
McLennan, S.M., 2001. Relationships between the trace element composition of sedimentary rocks and upper continental crust. G-cubed 2 (4).
McLennan, S.M., Taylor, S.R., Eriksson, K.A., 1983. Geochemistry of Archaean shales from the pilbara supergroup, western Australia. Geochem. Cosmochim. Acta 47, 1211–1222.
Mclennan, S.M., Nance, W.B., Taylor, S.R., 1980. Rare earth element-Thorium correlation in sedimentary rocks, and the composition of the continental crust. Geochem. Cosmochim. Acta 44, 1833–1839.
McLennan, S.M., Taylor, S.R., McCulloch, M.T., Maynard, J.B., 1990. Geochemical and Nd-Sr isotopic composition of deep-sea turbidites: crustal evolution and plate tectonic associations. Geochem. Cosmochim. Acta 54, 2015–2050.
Miall, A.D., 1977. Fluvial Sedimentology. Canadian Society of Petroleum Geologists, Calgary, p. 111.
Miall, A.D., 1988a. Architectural elements and bounding surfaces in fluvial deposits: anatomy of the Kagenta Formation (Lower Jurasssic), southwest Colorado. Sediment. Geol. 55, 233–262.
Miall, A.D., 1988b. Reservoir heterogeneities in fluvial sandstones: lessons from outcrop studies. AAPG (Am. Assoc. Pet. Geol.) Bull. 72 (6), 682–697.
Miall, A.D., 1992. Alluvial deposits. In: Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea Level Change. Geological Association of Canada, pp. 119–142.
Miall, A.D., 1996. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer Verlag Inc., Heidelberg, p. 582.
Murphy, J.B., 2000. Tectonic influence on sedimentation along the southern flank of the late paleozoic Magdalen Basin in the Canadian Appalachians: geochemical and isotopic constrains on the Horton group in the st. Marys basin, nova scotia. Geol. Soc. Am. Bull. 112, 997–1011.
Obaje, N.G., Attah, D.O., Opeloye, S.A., 2005. Geochemical evaluation of the hydrocarbon prospects of sedimentary basins in Northern Nigeria. Geochem. J. 40, 227–243.
Obaje, N.G., Balogun, D.O., Idris-Nda, A., Goro, I.A., Ibrahim, S.I., Musa, M.K., Dantata, S.H., Yusuf, I., Mamud-Dadi, N., Kolo, I.A., 2013. Preliminary integrated hydrocarbon prospectivity evaluation of the Bida basin in north Central Nigeria. Petrol. Trust Develop. J. 3 (2), 36–64.
Obaje, N.G., Musa, M.K., Odoma, A.N., Hamza, H., 2011. The Bida Basin in north-central Nigeria: sedimentology and petroleum geology. J. Petrol. Gas Exploration Res. 1 (1), 001-013.
Obaje, N.G., Wehner, G., Scheeder, G., Abubakar, M.B., Jauro, A., 2004. Hydrocarbon prospectivity of Nigeria's inland basins: from the viewpoint of organic geochemistry and organic petrology. AAPG (Am. Assoc. Pet. Geol.) Bull. 88 (3), 325–353.
Ojo, O.J., 2010. Occurrence of some Maastrichtian dinoflagellate cysts from the upper cretaceous sediments of the Bida basin, Nigeria: implications for age and paleoenvironments. Global J. Geol. Sci. 8, 217–230.
Ojo, O.J., 2012. Depositional environments and petrographic characteristics of Bida Formation around share-pategi, northern Bida basin, Nigeria. J. Geogr. Geol. 4 (1), 224–241.
Ojo, O.J., Akande, S.O., 2008. Microflora assemblage and paleoenvironment of the upper cretaceous Patti Formation, southern Bida basin, Nigeria. J. Min. Geol. 44, 71–81.
Ojo, O.J., Akande, S.O., 2009. Sedimentology and depositional environments of the Maastrichtian Patti Formation, south-eastern Bida basin, Nigeria. Cretac. Res. 30, 1415–1424.
Ojo, O.J., Jimoh, A.Y., Umelo, J.C., 2018. Geochemical and palynological studies of some Maastrichtian source rock intervals (Patti and Gombe formations) in Nigeria: implications for hydrocarbon prospectivity. AAPG Search Discov. (2019) Article #11185.
Ojo, S.B., Ajakaiye, D.E., 1989. Preliminary interpretation of gravity measurements in the middle Niger Basin area, Nigeria. In: Kogbe, C.A. (Ed.), Geology of Nigeria, second ed. Elizabethan Publishing Company, Lagos, pp. 347–358.
Olaniyan, O., Olobaniyi, S.B., 1995. Facies analysis of the Bida sandstone formation around Kajita, Nupe basin, Nigeria. J. Afr. Earth Sci. 23, 253–255.
Pettijohn, F.J., 1975. Sedimentary Rocks, third ed. Harper and Bros, New York, p. 628p.
Pettijohn, F.J., Potter, P.E., Siever, R., 1973. Sand and Sandstone. Springer-Verlag, New York, Heidelberg, Berlin, p. 618.
Potter, P.E., 1978. Petrology and chemistry of modern big river sands. J. Geol. 86, 423–449.
Rahman, M.J.J., Suzuki, S., 2007. Composition of neogene shales from the surma group, Bengal basin, Bangladesh: implications for provenance and tectonic setting. Austr. J. Earth Sci. 100, 54–64.
Rollinson, H., 1993. Using Geochemical Data: Evaluation, Presentation, Interpretation. Longman, p. 352p.
Roser, B.P., Korsch, R.J., 1986. Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio. J. Geol. 94, 635–650.
Roser, B.P., Korsch, R.J., 1988. Provenance signatures of sandstone-mudstone suites determined using discrimination function analysis of major-element data. Chem. Geol. 67, 119–139.
Rudnick, R., Gao, S., 2003. Composition of the continental crust. Treat. Geochem. 3, 1–64.
Scholle, P.A., 1979. A Color Illustrated Guide to Constituents, Textures, Cements, and Porosities of Sandstones and Associated Rocks: Tulsa, Oklahoma. American Association of Petroleum Geologists, Memoir, p. 201.
Sugitani, K., Horiuchi, Y., Adachi, M., Sugisaki, R., 1996. Anomalously low Al_2O_3/TiO_2 values for Archean cherts from the Pilbara Block, Western Australia: possible evidence for extensive chemical weathering on the early earth. Precambrian Res. 80 (1–2), 49–75.
Suttner, L.J., Basu, A., Mack, G.H., 1981. Climate and the origin of quartz arenites. J. Sediment. Petrol. 5, 1235–1245.
Taylor, S.R., McLennan, S.M., 1985. The Continental Crust: its Composition and Evolution. Blackwell Scientific Publications, Oxford, p. 312p.
Tucker E., M., 1996. Sedimentary petrology: An introduction to the origin of sedimentary rocks, 2nd. Wiley-Blackwell, pp. 1–272.
Udensi, E.E., Osazuwa, I.B., 2004. Spectra determination of depths to Magnetic rocks under the Nupe basin, Nigeria. Nigerian Assoc. Petrol. Explor. Bull. 17, 22–37.
Weltje, G.J., Eynatten, H.V., 2004. Quantitative provenance analysis of sediments: review and outlook. Sediment. Geol. 171 (1–4), 1–11.
Weltje, G.J., Meijer, X.D., de Boer, P.L., 1998. Stratigraphic inversion of siliciclastic basin fills: a note on the distinction between supply signals resulting from tectonic and climatic forcing. Basin Res. 10, 129–153.
Whiteman, A.J., 1982. Nigeria: It's Petroleum Geology: Resources and Potential, vols. 1–2. Graham and Trotman, London, p. 394.
Wronkiewicz, D.J., Condie, K.C., 1990. Geochemistry and provenance of sediments from the pongola supergroup, South Africa: evidence for a 3.0-Ga-old continental craton. Geochem. Cosmochim. Acta 53, 1537–1549.
Yamamoto, K., Sugisaki, R., Arai, F., 1986. Chemical aspects of alteration of acidic tuffs and their application to siliceous deposits. Chem. Geol. 55, 61–75.