



PROVENANCE AND TECTONIC SETTING OF THE BIMA SANDSTONE WITHIN THE YOLA ARM OF THE UPPER BENUE TROUGH, NORTHEASTERN NIGERIA

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ABSTRACT

This study focuses on the analysis of the Bima Sandstone within the Yola arm of the Upper Benue Trough in order to establish provenance and the tectonic setting of the regions where the sediments were derived. Extensive fieldwork was conducted and samples of the Bima Sandstone were systematically collected for laboratory analyses – including petrographic and X-ray diffraction (XRD) analyses. Quantitative assessment of detrital minerals, revealed that the clastic sediments are primarily composed of quartz, feldspars, and fragments of metamorphic and igneous rocks. Quartz comprises approximately 70-87% of the detrital framework grains, followed by feldspar at 2-6%, and lithic fragment 2-5%. These sandstones have been classified as subarkose, Quartz arenites, and sublitharenite, with a majority (>70%) falling within the subarkose/Quartz arenite category. Both petrographic and XRD analyses suggest that the sandstones originated from granitic and metamorphic rock sources. The QFL (Quartz-feldspar-lithic fragments) ternary diagrams indicate that these sandstones were derived from continental quartzose sedimentary source rocks, suggesting a craton interior or transitional continental setting.

Keywords: Bima Sandstone, Petrography, Provenance, Upper Benue Trough, X-ray diffraction, Yola arm.

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INTRODUCTION

Sandstones serve as valuable indicators for deducing provenance and ancient tectonic settings. They offer detailed insights into the origin, sediment transport, and the interplay of physical and chemical processes from source areas to depositional basins. Petrographic analysis of sandstones can unveil valuable information regarding the provenance of detrital components, notwithstanding the influence of processes like weathering, transportation, and diagenesis [1]. As documented by Dickinson [1], the tectonic setting of sedimentary basins significantly impacts their composition. Different tectonic environments exhibit distinct mineral combinations, which are indicative of specific sedimentary processes [2]. This study therefore, uses petrographic and XRD analyses to unravel the mineralogical composition of the Bima Sandstones, infer their provenance and interpret the tectonic setting from which the sediments were derived

Geology of the Upper Benue Trough

The Benue Trough, is a NorthEast (NE) trending basin (Figure 1a) that is divided into the ‘Lower Benue Trough - LBT’, ‘Middle Benue Trough - MBT’, and ‘Upper Benue Trough - UBT’ [3, 4]. There are no distinct boundaries that separates the individual sections of the trough, but significant localities representing depocenters within each section have been meticulously cataloged by authors like Petters [5], Nwajide [6] and Idowu [7].

The Upper Benue Trough where the study area is located (Figure 1a), bifurcates into two arms: the Gongola arm, striking N-S toward Lake Chad, and the

E-W Yola arm extending towards Yola and Cameroon, following the path of the River Benue [8]. In both arms of the Upper Benue Trough, the basal sedimentary unit is the continental Bima Sandstone, which unconformably overlays the PreCambrian basement, and represents the oldest known Cretaceous sediment in the region [8]. These sandstones are interpreted as deposits from alluvial fan to braided river systems (Figure 2)[9].

Subsequently, episodes of marine transgression led to the deposition of the Yolde, Dukul, Jessu, Sekule, and Numanha sedimentary formations, which are prominent in the Upper Benue Trough's Yola arm (Figure 2). The Bima Sandstone is further subdivided into Lower, Middle, and Upper units by Carter *et al.* [3], with Guiraud [10] introducing lithostratigraphic terms, B1, B2, and B3, to informally designate major sedimentary units associated with tectonic events during the early Cretaceous. The Lower Bima (B1) is the oldest, characterized by coarse-grained sediments and remarkable thickness. The Middle Bima (B2) contains gravelly deposits and coarse-grained sandstone, separated at its base by a regional unconformity from the Lower Bima (B1). The youngest unit, the Upper Bima (B3), comprises cross-bedded sandy deposits, exhibiting evidence of pre-consolidation or soft-sediment deformation [11]. This study focuses on the Upper,

Middle, and Lower Bima Santone units, which prominently outcrop in the study area.

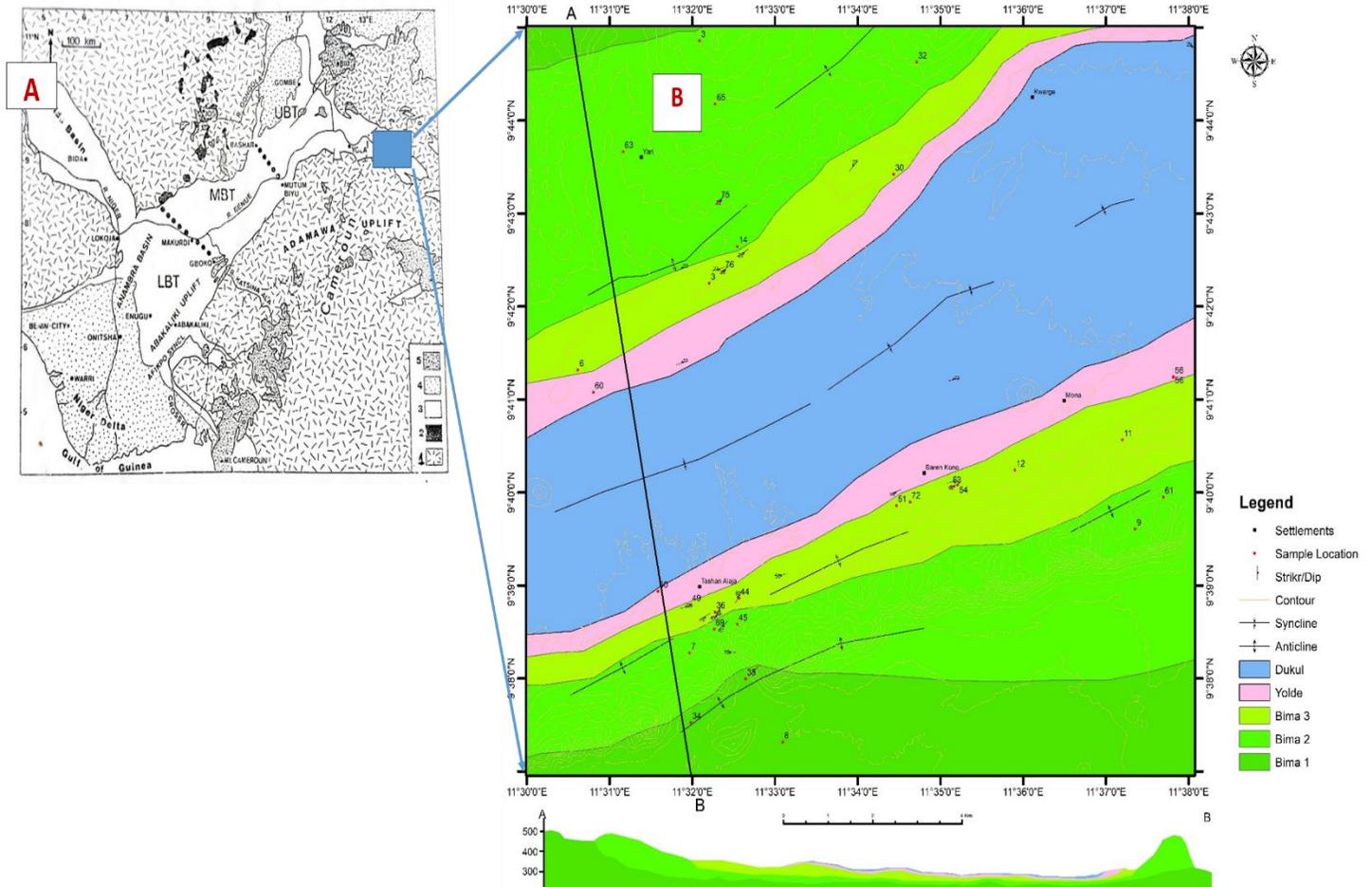


Figure 1: (a) Geological map of the Benue Trough and adjacent areas showing the approximate location of the study area. LBT, lower Benue Trough, MBT, middle Benue Trough, UBT. Upper Benue Trough. 1. PreCambrian 2. Jurassic “younger granites”, 3. Cretaceous, 4. Post Cretaceous sediments. 5. Cainozoic- recent basalts [9]; (b) Geologic map of the study area showing outcrop distribution of the different units of Bima Sandstone.

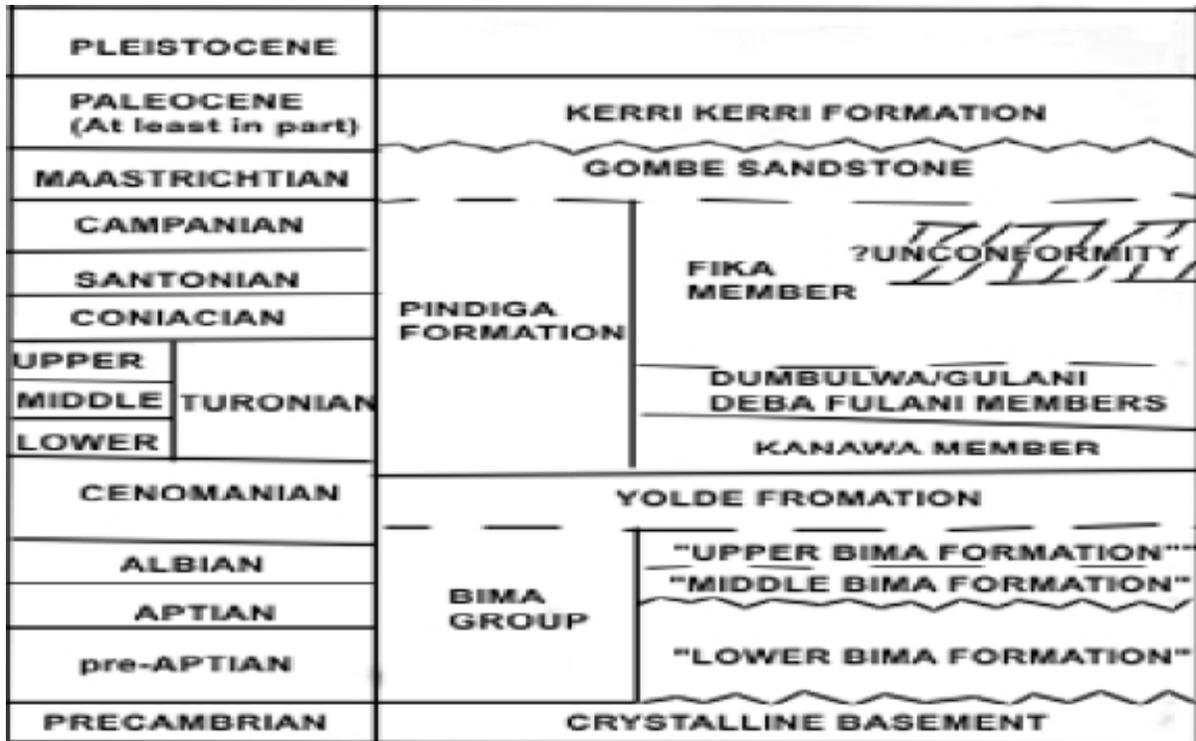


Figure 2: Stratigraphy successions of the Upper Benue Trough [9]

MATERIALS AND METHODS

In this study, we analyzed a set of 12 sandstone samples obtained from the Upper, Middle and Lower Bima Sandstone units within the study area, (Figure 1b) 9° 37' 00'' N to 9° 45' 00''N and 11° 30' 00''E to 11° 38' 00''E part of Guyuk Sheet 174. These samples were carefully selected from the larger collection of outcrop samples for detailed examination. To facilitate our analysis, we prepared representative thin sections of various sandstone types, which were subsequently studied under an optical microscope including modal composition analysis.

To distinguish between samples from different subdivisions of the Bima Sandstone (Lower, Middle, and Upper), we assigned prefixes B1, B2, B3 to them accordingly. It is important to acknowledge that the limited number of samples from each formation might not entirely encapsulate the heterogeneity of the sedimentary sequence. Nonetheless, we made a concerted effort to gather a diverse set of samples from various locations within each of these areas which were used to prepare thin sections for further examination. Our selection of representative thin sections was guided by variations in grain-size distribution, textural characteristics, sedimentary facies, petrographic composition, and lithology. This ensured that our chosen samples effectively represented the entirety of sandstone diversity within the study area.

For the determination of framework components, we adhered to the nomenclature suggested by Dickinson [2], [1], and [12]. Mineral elements within the sandstones were categorized into monocrystalline quartz (mQ), polycrystalline quartz (PQ), Microcline feldspar (Mf), plagioclase (Pf), and lithic/rock fragments (Rf). Modal analysis considered Quartz, Feldspar, lithic fragments, mica, and heavy minerals, while excluding other clays and authigenic accessory minerals. To classify these sandstones, we recalculated their framework detrital modes to 100% and plotted Q-F-L (Quartz-feldspar-lithic fragments) ternary graphs. For this purpose, we employed the Q-F-L ternary diagrams proposed by Petijohn [13] and Folk [14]. Additionally, we employed X-Ray Diffraction (XRD) to determine the mineralogical composition of the sandstones, to provide further support and confirmation of the petrographic analysis.

RESULTS AND DISCUSSION

Petrographic analysis

The textural and mineralogical attributes of detrital sediments are influenced by their parent rocks, diagenetic processes occurring during deposition, and subsequent post-depositional transformations after sediment transportation from source to depositional site. The continuous reworking of sediments results in lithic fragments and distinct minerals, aiding in the

identification of their parent rocks. The composition of the studied samples is presented as follows:

Quartz, constitutes a significant proportion of the detrital grains. The quartz content in the Lower, Middle, and Upper Bima Sandstones from petrographic analysis range from 76-84%, 70-81%, and 80-87%, respectively. These sandstones contain both monocrystalline and polycrystalline quartz grains, with monocrystalline quartz averaging 52%, 44%, and 59% in the B1, B2, and B3 sandstones, respectively.

The Quartz grains display angular to sub-angular shapes, poor sorting. Various grain contacts are formed by pressure solution and compaction indicating mineralogical maturity. Monocrystalline quartz grains (Qm) in the sandstones are sub-angular to sub-round, comprising undulose and non-undulose varieties. Qp grains consist mainly of non-oriented crystallites, typically two or three per grain, with straight to undulose extinction. Inclusions are present within both Qm and Qp grains. The presence of both polycrystalline and monocrystalline quartz, along with feldspar grains, suggests limited transportation separation [15]. Based on the quartz types classification of Folk [16], monocrystalline quartz grains originate from plutonic, hydrothermal, and recycled sedimentary sources, while polycrystalline quartz grains are recrystallized metamorphic types.

Feldspar minerals found in the sandstones include alkali feldspar (orthoclase and microcline) and plagioclase feldspar (albite). K-feldspar dominates the feldspar population relative to plagioclase varieties (plagioclase, orthoclase, and microcline). These feldspar grains are mainly sub-angular to sub-round in shape and exhibit twinning, including albite and albite-Carlsbad twinning, with microcline characterized by cross-hatched twinning. Some feldspar grains have undergone alteration to kaolinite, muscovite, or replacement by calcite. Albite and orthoclase are the dominant feldspar minerals, occurring in twinned and untwinned forms.

Lithic fragments make up a smaller portion of the sandstones compared to quartz and feldspars. These fragments consist of metamorphic, sedimentary, and igneous rock clasts and average approximately 3.6%, 4.3%, and 3.2% in the Upper, Middle, and Lower Bima Sandstones, respectively. Lithic fragments tend to break

into other mineral components, while argillaceous grains can be compacted and deformed.

In essence, petrographic analyses revealed that the samples primarily consist of quartz, feldspar, and rock fragments, with over 75% of the total framework grains falling into this category (Figure 3). The grains exhibit varying degrees of angularity, sub-angular, and roundness, with a prevalence of angular to sub-angular shapes. They grains are also poor sorted. Grain contacts in the samples include point, long, sutured, and concave-convex contacts, typically resulting from pressure solution and compaction processes (Figure 3). Given the relative scarcity of feldspars and rock fragments compared to quartz, our provenance analysis follows the interpretation methods proposed by Folk [14] and Petijohn [13]. The framework grains encompass monocrystalline quartz (Qm), polycrystalline quartz (Qp), K-feldspar, plagioclase, and rock fragments. The presence of both polycrystalline and monocrystalline quartz suggests mixed influences from igneous and metamorphic sources, possibly due to incomplete separation during transportation.

Considering the genetic and empirical classification of the quartz types by Folk [16], these monocrystalline quartz grains are predominantly associated with plutonic, hydrothermal, and recycled sedimentary sources, indicating a granitic source for these sediments [17, 23]. On the other hand, Dabbagh, & Rogers [18],—propose that such grains may have formed through the disaggregation of original polycrystalline quartz during high-energy or long-distance transport from metamorphic sources. Some monocrystalline and polycrystalline quartz grains exhibit undulatory extinction and inter-crystalline suturing, suggesting a metamorphic rock origin, while others display uniform extinction and overgrowth. In a few instances, muscovite is present, indicating potential igneous or metamorphic sources [17] and [19]. The presence of microcline suggests a source rock of low-grade metamorphic terrain and alkali-rich granites [20]. Orthoclase in the sandstones points to plutonic and metamorphic origins, although its percentage is relatively low compared to other detrital components. Mica is commonly derived from metamorphic and igneous sources [20] and [19].

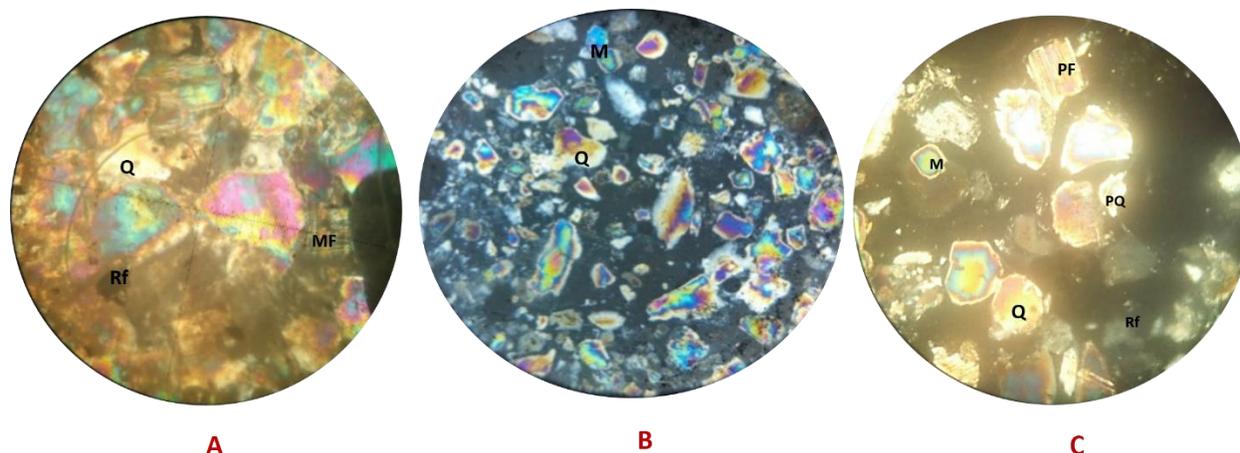


Figure 3: Photomicrograph of minerals under XPL lights. Q-Quartz, PF- Plagioclase Feldspar MF-Microcline Feldspar, M-Muscovite, RF-Rock fragments

Mineralogy and modal composition

The mineralogical composition of the sandstones analyzed using X-Ray Diffraction (XRD) is summarized in Table 1, and the distinct mineral phases are illustrated in Figure 4. The findings indicate the occurrence of the subsequent minerals in the examined Bima Sandstone: Quartz, Kaolinite, Feldspars, Muscovite, and Dickite. In the Lower Bima Sandstone, quartz constitutes the predominant mineral (53.00-73.69%), accompanied by a substantial presence of kaolinite (31.00-37.52%), with microcline detected in trace amounts. Contrastingly, the Middle Bima Sandstone is made up of quartz (30.25-46.51%) and Kaolinite (11.88-53.70%), with microcline occurring in minor proportions. The Upper Bima Sandstone primarily comprises quartz (55-75%), but also has dickite mineral which were not seen in the other Bima units.

Sandstone Classification

Sandstone classification techniques, crucial for geological analysis, commonly employ a combination of texture and mineralogy, as endorsed by Dickinson [1] and Pettijohn [13]. Folk's [16] classification system provides valuable insights into provenance, where the rock's nomenclature reflects its documented

composition [21]. Dickinson [1] proposed the use of ternary diagrams as effective tools for distinguishing terrigenous deposits in various plate tectonic settings, thereby enabling tectonic reconstructions. As emphasized by Johnson M.R. [22], the relative abundance of quartz compared to feldspar, micas, and matrix minerals in a sample offers insights into sediment maturity concerning weathering and transportation processes.

Recalculated framework grain values are plotted on ternary diagrams such as Q-F-L, following Pettijohn [13] based on their relative proportions and the Q-F-R plot proposed by Folk [14] for sandstone classification providing insights into their origin and depositional history. In the case of the Lower and Upper Bima Sandstone samples within the study area, they fall mostly within the Quartz-arenite field, while the Middle Bima Sandstone samples are primarily located in the sub-arkose field (see Figure 5A). Similarly, when using Folk's [16] Q-F-R ternary plot for sandstone classification, the Lower and Upper Bima Sandstone samples cluster in the quartz-arenite field, with the Middle Bima Sandstone samples occupying the sub-arkose region (Figure 5B).

Table 1: Summary of minerals presented from XRD analysis

Sample	Mineral	Formula
B1a	- Quartz (abundant)	- SiO ₂
	- Microcline	- KAlSi ₃ O ₈
B1b	- Kaolinite	-Al ₂ (Si ₂ O ₅)(OH) ₄
	- Orthoclase,	-(NaAl Si ₃ O ₈).
B1bs	-Albite	
B2a	- Quartz (abundant)	- SiO ₂
	- Kaolinite	-Al ₂ (Si ₂ O ₅)(OH) ₄
B2b	-Microcline	- KAlSi ₃ O ₈
B2bs	-Quartz	- SiO ₂
	-Muscovite	- KalSi ₃ O ₈
	-Kaolinite.	-Al ₂ (Si ₂ O ₅)(OH) ₄
B3bs	-Quartz	- SiO ₂
	-Muscovite	- KalSi ₃ O ₈
B3b	- Quartz (abundant)	- SiO ₂
	-Microcline	- KAlSi ₃ O ₈
	-Dickite.	-Al ₂ Si ₂ O ₅ (OH) ₄

Table 2: Detrital grains modes and the derived QFL indices

Formation	Sample	Quartz			Feldspar			Rock fragment	Cement %	Normalized (100%)		
		Qm	Qp	Qt	Fm	Fp	Ft	LT		Q	F	L
Lower Bima	B1A	49	10	59	0	1	1	3	10	84	3	3
	B1B	58	18	76	0	3	3	2	15	80	3	2
	CB1A	50	3	53	1	3	4	2	15	76	6	3
Middle Bima	B2A	44	3	47	0	0	3	3	10	81	5	4
	B2B	52	7	59	3	4	7	2	15	74	9	3
	CB2A	52	6	58	3	2	5	3	8	81	7	4
	CB2B	40	3	43	1	3	4	2	20	70	7	3
Upper Bima	B3A	70	6	76	3	4	7	2	8	87	3	2
	B3B	52	9	61	1	0	1	4	20	74	1	5
	CB3A	55	4	59	2	0	2	3	10	83	3	4
	CB3B	60	10	70	0	0	0	2	18	80	2	2

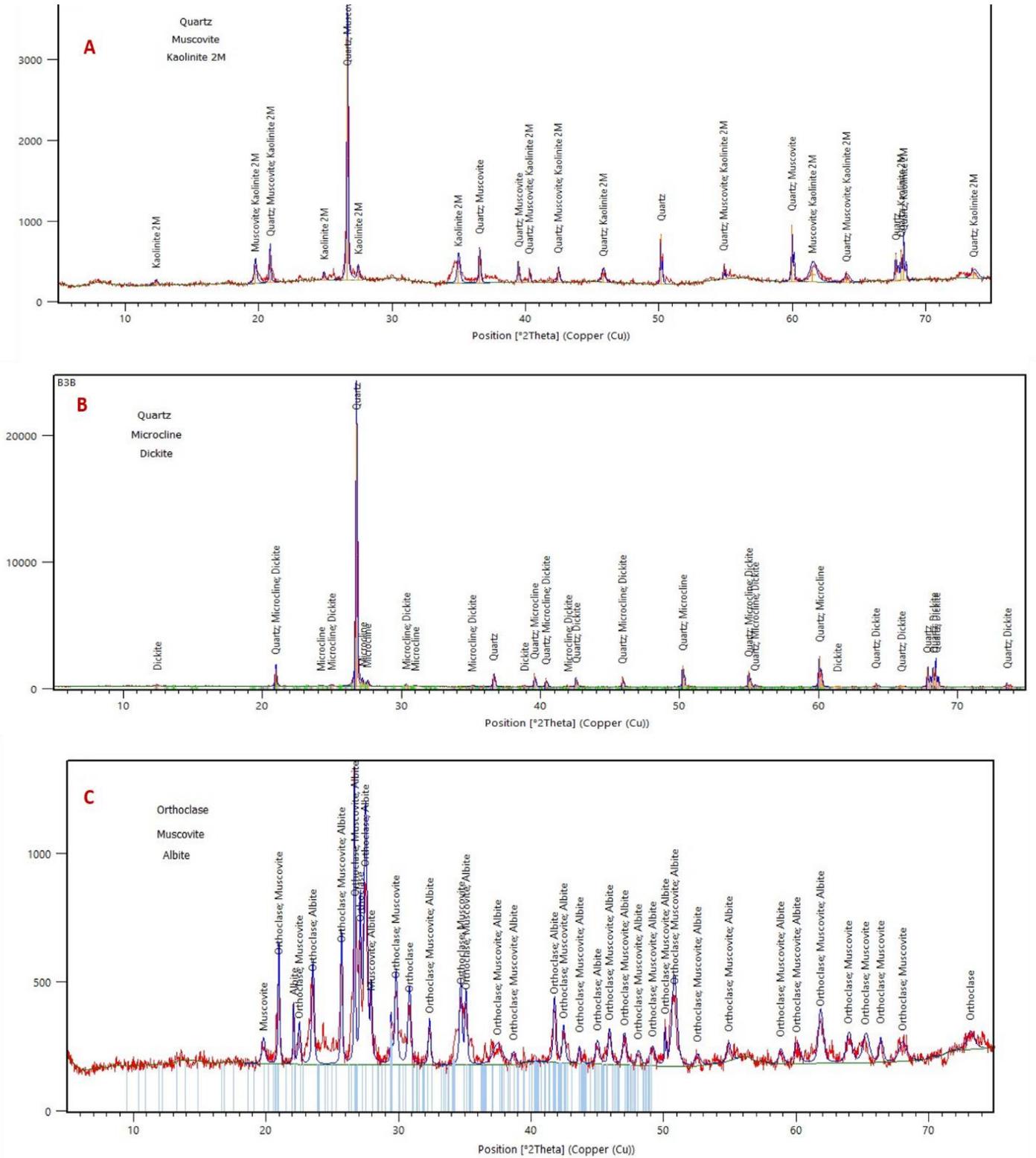


Figure 4: Diffractogram of the peaks of different minerals present in the Bima Sandstone

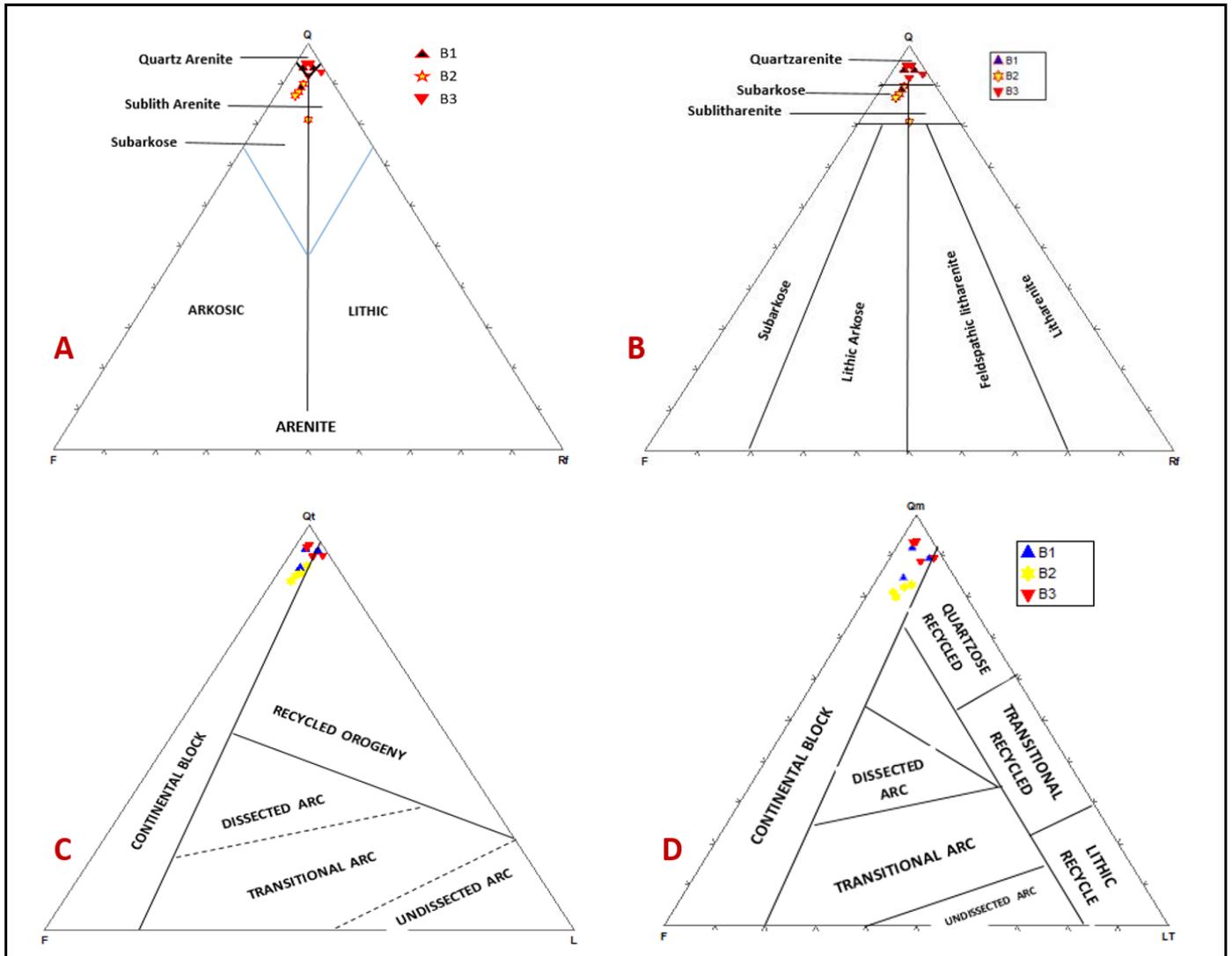


Figure 5: Q-F-L mineralogical classification plot (a) after Pettijohn, (1970)[13] (b) Q-F-R plot after Folk (1980)[14] QtFL (c) and QmFLt (d) ternary diagrams for the Bima Sandstone, after [12]and[2].

Provenance and Tectonic Setting

These workers Dickinson and Suczek [2], Dickinson [1], and Dickinson *et al.* [12] have associated the compositions of detrital sandstones with various provenance types (e.g., stable cratons, basement uplifts, magmatic arcs, and recycled orogeny) by employing Qt-F-L and Qm-F-Lt ternary diagrams. Sandstone suites originating from distinct plate tectonic settings consistently exhibit unique compositions, clearly demarcated within discrete regions on the Qt-F-L and Qm-F-Lt diagrams [2]. These diagrams have also been employed to differentiate tectonic environments for the Bima Sandstones.

In the Qt-F-L ternary diagram, the majority of analyzed sandstones are situated within continental block fields (Lower and Middle Bima), with only a

minority positioned in the margin of the recycled orogenic fields (Upper Bima) (Figure 5C). The presence of a low percentage of unstable grains (feldspar and other rock fragments), the prevalence of monocrystalline quartz, and instances of feldspar grain alteration collectively suggest that these Bima Sandstones experienced relatively short-distance transport from their source. The Qm-P-K plot [2] for clastic sedimentary rocks illustrates an increasing maturity trend in the sediments (Figure 5D). Furthermore, based on the plot proposed by Dickinson *et al.* [12], a continental block provenance is indicated, with clustering around the Qt and Qm apex, implying a source within a stable continental craton, particularly the cratonic interior. The primary sources for quartzose sands derived from cratons are presumed to be low-lying

granitic and gneissic outcrops, supplemented by the recycling of associated flat-lying platform sediments. These sands are believed to have accumulated as platform successions deposited within continental interiors and subsequently transported predominantly to passive continental margins [2]. This continental block represents tectonically stable regions, which are remnants of ancient orogenic belts that have eroded to their deep-seated roots and lack any residual relict genetic relief [1].

CONCLUSION

In conclusion, the petrographic and mineralogical investigations of the sandstones within the lower, middle, and upper Bima Sandstone units have yielded a classification of these sediments into Quartz arenite, sub-litharenite, and subarkose categories. Notably, these sediments exhibit a consistent mineral composition, suggesting a common source area. The sandstones display a predominant quartz content ranging from 62% to 91%, while feldspar components remain relatively low, at less than 16%. The presence of relatively unaltered feldspar in certain sandstone samples indicates favorable climatic conditions that facilitated limited chemical weathering, thus preserving less stable mineral phases.

Both petrographic and X-ray diffraction (XRD) analyses point to a granitic to metamorphic rock origin which were majorly derived and sourced from a passive continental margin, implying deposition in plate interiors within a stable or intracratonic basin. Consequently, the source of the examined sediments can be attributed to a stable cratonic region. This inferred provenance aligns with the tectonic events occurring in the West and Central African Rift System (WCARS) during the Early Cretaceous.

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