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Granulometric, Heavy Mineral and Petrography Investigation of The Textural Properties, Paleoenvironment, and Classification of Wurno Sandstone, Sokoto Basin, Northwestern Nigeria

Ola-Buraimo A. Olatunji. and Musa A. Sadique

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Abstract: *Field outcrop description, granulometry, heavy-mineral, and petrographic investigations were carried out on Wurno Formation sediments to determine the textural characteristics, textural maturity, paleoenvironment of deposition, and transportation history of the sandstone samples. Sieving method in which various sieve sizes were placed on a sieve shaker and agitated for 15 minutes; retained particles were measured and entered into software to generate textural statistical measures. Heavy minerals were separated by the use of bromoform, while the petrographic analysis carried out was determined by the modal counts of quartz, feldspar, and rock fragments to determine the angularity of the grains. Lithostratigraphic succession of Runjin Beau outcrops of the Wurno Formation is characterised by bioturbated, herringbone structure unconsolidated medium sandstone, overlain by coarser light brownish sandstone, and clayey sandstone successively. The clayey sandstone is overlain by an intercalation of variegated friable sandstone and brownish laminated sandstone of different water current regimes. Gradational contact separates the laminated brownish sandstone from the overlying lignitic sandstone of a lagoonal deposit. This is overlain by orange sandstone with clay flasers, angular unconformably overlain by cross-laminated lignitic fine sandstone, capped by orange sandstone and folded ferruginized ironstone. Grain size of the samples varies from 1.37-2.13 (av.1.85), classified into the medium grain size class, except sample SRU2-T defined as fine-grained sediment. Sorting values vary from 0.55-1.035 (av. 0.72) of moderately well-sorted and moderately sorted classes. The grain size and sorting values indicate that the sediments were transported far away from the source and subjected to winnowing under multiple current effects. The skewness types are nearly symmetrical (0.04 to -0.07), negatively skewed (-0.179 to 0.22), and positively skewed (0.14). The Kurtosis are leptokurtic (1.18-1.23) and very leptokurtic (1.52-1.6) of an unimodal source. Bivariate plots indicate beach deposits except for sample SRU2 M2. The multivariate indices of -8.76 to -7.08 are indicative of an intertidal to tidal shelf depositional environment. ZTR indices vary from 47.3-56.4 %, indicative of mineralogically submature sediments. Modal count of quartz, feldspar, and rock fragments indicated two sediment types; quartz arenite, texturally mature and sublitharenite, which is texturally submature.*

Keywords: *Lignitic sandstone, Angular unconformity, Folded ferruginized ironstone, Medium grain, Moderately well sorted, Intertidal to Tidal Shelf*

Ola-Buraimo A. Olatunji*
Department of Geology, Federal University, Binin Kebbi, Nigeria
Email: olatunji.ola-buraimo@fubk.edu.ng
https://orcid.org/0000-0001-9601-1545

Musa A. Sadique
Department of Geology, Federal University Binin Kebbi, Nigeria
Email: mosasadeeq@gmail.com

1.0 Introduction

The Sokoto Basin is located in northwestern Nigeria, and it is described as an extension to the southern segment of the Iullemmeden Basin, which covers Niger, Mali, Benin, and

Algeria (Whiteman, 1982). The Sokoto Basin contains a thick succession of Middle Cretaceous to Tertiary sediments deposited during multiple phases of marine transgression and regression associated with the opening of the South Atlantic and Mediterranean seas during the Middle Cretaceous (Fairhead & Binks, 1991; Kogbe, 1989, 1981; Genik, 1992; Nwajide, 2013; Ola-Buraimo & Mohammed, 2024). The Gundumi and Illo Formations represent the oldest sedimentary units in the basin and were deposited unconformably on the Precambrian Basement Complex Rima Group sediments comprising the Taloka, Dukamaje, and Wurno Formations were deposited on the Gundumi and Illo Formations during uncertain Maastrichtian time (Lawal, 2023; Hamidu *et al*. 2024; Ola-Buraimo & Ibrahim, 2026, in press). Successive formations deposited on the youngest Rima Group sediment (Wurno Formation) are Dange, Kalambaina, and Gamba Formations (Kogbe, 1976, 1989; Obiosio *et al*., 1998; Obaje *et al*. 2013); Lawal & Hassan, 2023). They vary in relative age from Maastrichtian to Middle Eocene (Ola-Buraimo and Abdulhakeem, 2023, unpublished; Ola-Buraimo and Mohammed, 2024; Ola-Buraimo & Mesharck, 2024). The youngest formation in the basin is Gwandu Formation, recently dated as Early Miocene, deposited in continental and marine environments (Ola-Buraimo and Haidara, 2022; Ola-Buraimo *et al*., 2023).

The Wurno Formation is the stratigraphic sequence of interest to this study. The Wurno Formation remains poorly documented in terms of detailed sedimentological characterization and biostratigraphic constraints. Recently documented literature on it shows that the Wurno Formation is characterized by laminated siltstone, sandstone, and mudstone or shale deposited in intertidal flat environment (Lawal & Yamusa, 2025 unpublished). Field observations further described it to contain siltstone and moderate to well sorted fine sandstone lenses as a result of rapid marine transgression (Lawal and Yamusa, 2025).

Despite these studies, an integrated evaluation combining detailed granulometric statistics, heavy mineral assemblages, and petrographic analysis to constrain sediment maturity, provenance, and tidal influence on depositional environments of the Wurno Formation remains limit

The main aim of this study is to provide an integrated sedimentological interpretation of the Wurno Formation using granulometric, heavy mineral, and petrographic data to reconstruct depositional environment, sediment maturity, and transport history. This research is an encompassing investigation on the Wurno Formation based on lithostratigraphic field observations, textural, and mineralogical characteristics, and petrographic study. This approach differs from earlier studies, which largely emphasized field descriptions alone (Abdulganiyu, 2025) or combined field geology with limited thin-section and XRD analyses (Lawal and Yamusa, 2025), without comprehensive integration of granulometric and heavy mineral data (Abdulganiyu, 2025). The Wurno Formation study was undertaken to determine the textural and mineralogical properties and maturity, paleoenvironment of deposition, and the effect of tidal magnitude as a factor responsible for various environmental settings. The study is also important in characterizing the sandstone facies as a hydrocarbon reservoir or groundwater aquifer potential in the Sokoto Basin because of its stratigraphic position to the underlying probable marine source rocks of the Dukamaje Formation.

The findings are expected to improve understanding of tidal depositional systems in the Sokoto Basin and provide baseline data for evaluating the hydrocarbon reservoir and groundwater aquifer potential of the Wurno Sandstone

The geological field study was carried out in Runjin Beau Village, located in Wammako Local Government Area, Sokoto State, Nigeria. The investigated area lies between Latitude 13°01′14″N and Longitude 5°07′56″E (Fig. 1). The area is accessible by roads and footpaths to other adjoining villages (Fig. 1).

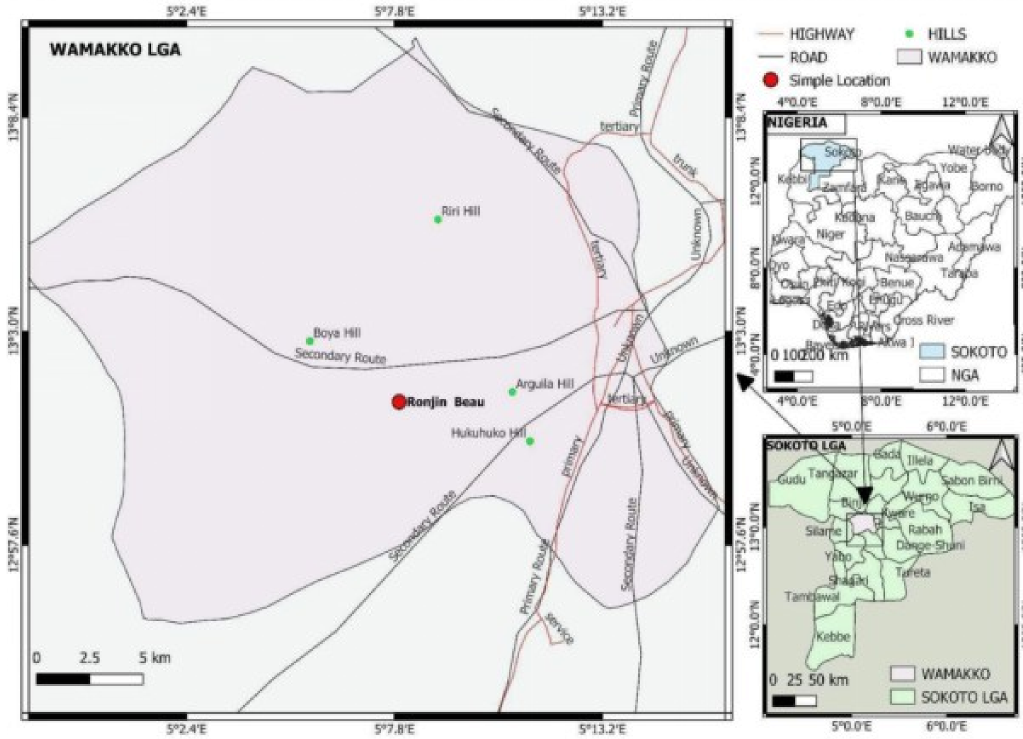

Fig. 1: Location map of the Runjin Beau study area

2.0 Methodology

2.1 Fieldwork and Lithologic Logging

Fieldwork materials such as a geological hammer, field notebook, pencil, marker pen, hand lens, base map, compass-clinometer, GPS, measuring tape, masking tape, ruler, 10% dilute hydrochloric acid, and camera were used for the fieldwork exercise. Field studies and logging of bed succession were carried out based on colour, rock type, mineral composition, textural parameters, sedimentary structures, fossil content, accessory minerals, and diagenetic features following Oladimeji & Ola-Buraimo (2022b)

2.2 Granulometric (Sieve) Analysis

Laboratory sieve analysis was carried out on dry, disaggregated sediment samples of 100 g each, weighed using an analytical balance. A set of sieves of various mesh sizes was stacked and arranged from the coarsest (2 mm) at the top to 63 µm mesh, with a pan at the bottom. The sieve stack was tightly clamped onto a mechanical sieve shaker and agitated for 10 minutes (Lindholm, 1987). After agitation, grains retained in each sieve were weighed and recorded. These procedures were carried out for each of the five samples used for this study. Basic data, where the mass of the sediments in a set of sieves for a sample was input in Microsoft Excel format and processed using GRADISTAT software.to generate a spreadsheet, graphical output (Blott, 2000). Statistical parameters, including mean grain size, sorting (standard deviation), skewness, and kurtosis, were computed in logarithmic units using the phi (φ) scale of Krumbein and Pettijohn (1938).

Linear interpolation was applied to compute grain-size parameters following the method of Folk and Ward (1959). Therefore, physical descriptions in terms of textural parameters, such as moderately sorted, fine to medium grain sizes, were adopted after the work of Folk (1954). The grain size classification into size fractions was generated, modified after Udden (1914) and Wentworth (1922). The grain sizes of individual samples were produced on a ternary diagram to classify the sediments into different sandstone classes (Blott, 2000).

2.3 Petrographic Analysis

Petrographic sample preparation involved washing 100 g of sandstone sample with detergent under gently running tap water through a 63 µm mesh to remove clay particles. After thorough washing, the sample was dried in an oven at high temperature. The dried sample was mounted on glass slides using Canada balsam and ground to standard thickness before examination under a petrographic microscope. Modal analysis was carried out using the point-counting method on at least 300 points per thin section.

2.4 Heavy Mineral Analysis

Heavy mineral analysis involved disaggregating sediment samples, after which 10 g of each sample was weighed in duplicate.. The sample was washed to remove the clay-size fraction using the BS test of 63 µm aperture (Joshua and Oyebanjo, 2009). The samples were treated with 37% hydrochloric acid diluted in a 1:1 ratio and heated for approximately 10 minutes in a fume cupboard to remove iron coatings and carbonate cement. The treated samples were washed, dried, and subjected to heavy mineral separation using the gravity method with bromoform (specific gravity = 2.8 g/cm³). The extracted minerals were rinsed, dried, and then mounted on a glass slide for a heavy minerals study under a binocular microscope (Mange and Maurer, 1992).

3.0 Result and Interpretation

3.1 Lithological field description

The area investigated is Runjin Beau, located in Wammako Local Government Area, Sokoto State. The outcrop at Runji Beau is located at latitude 13° 1′ 18″ N and longitude 05° 7′ 56″ E, with an elevation of approximately 280 m above sea level.

The lithological succession of the Runjin Beau outcrop of the Wurno Formation is composed of various layers characterized by different features. The basal bed of the outcrop is composed of unconsolidated, herringbone-structured, light brownish sandstone of a shoreface deposit. This is overlain by coarser light brownish sandstone. Overlying this layer is a clayey sandstone bed that is fairly bioturbated. The fairly bioturbated clayey sandstone is overlain by brownish sandstone, characterised by ichnofossils and burrows. This layer is overlain by an intercalation of variegated milky to yellowish and milky to purplish under compacted, friable sandstone with dispersed load cast structure. The burrows are vertical, horizontal and inclined with a distinctive herringbone structure, indicative of high energy tidal marine environment of deposition.

The herringbone structure resulted from tidal current flow in opposite directions at different times. Such circumstances of bi-polar cross-stratification usually form in a single vertical section as a result of directional migration of ripples or dunes produced by tidal current (Dalrymple & Choi, 2007; Nwajide, 1980; Adeigbe *et al.,* 2014). It is overlain by brownish laminated sandstone of different water current regimes. Gradational contact separates the laminated brownish sandstone of a possible marginal marine deposit from the overlying lignitic sandstone of a foreshore deposit (Reijer, 1996).

The lignitic fine sandstone is characterized by an intertonguing relationship which wedges out in opposite directions. The lignitic sandstone stains the hand with black colour when rubbed. This is overlain by orange sandstone with clay flasers. Angular unconformity separates the lignitic fine sandstone from the overlying orange sandstone. The litho-section is capped by folded ferruginized ironstone, which was possibly deposited in a stagnated, concentrated iron-rich mineralised condition, folded as a result of local internal gravity flow. The sedimentary structures attributed to the Wurno Formation are ichnofossil, bioturbation in the form of burrows, others are herringbone structure, fold, joint and angular unconformity of a wash over channel deposit (Reijer, 1996; Plate 6).

3.2 Sieve Analysis Result

The results obtained from sieve analysis carried out on the five samples were presented in Table 1. The cumulative weights obtained for the five samples were presented in Table 2. The raw data obtained from the sieving exercise were plotted using the software for deducing textural parameters and statistical variables such as the mean, standard deviation (sorting), skewness and kurtosis. Cumulative frequency curve from which the interpretation of the textural parameters was derived, as shown in Figs. 2, 4, 6, 8, and 10. Histogram plots show the distribution of grain sizes relative to one another, as shown in Figs. 3, 5, 7, 9, and 11.

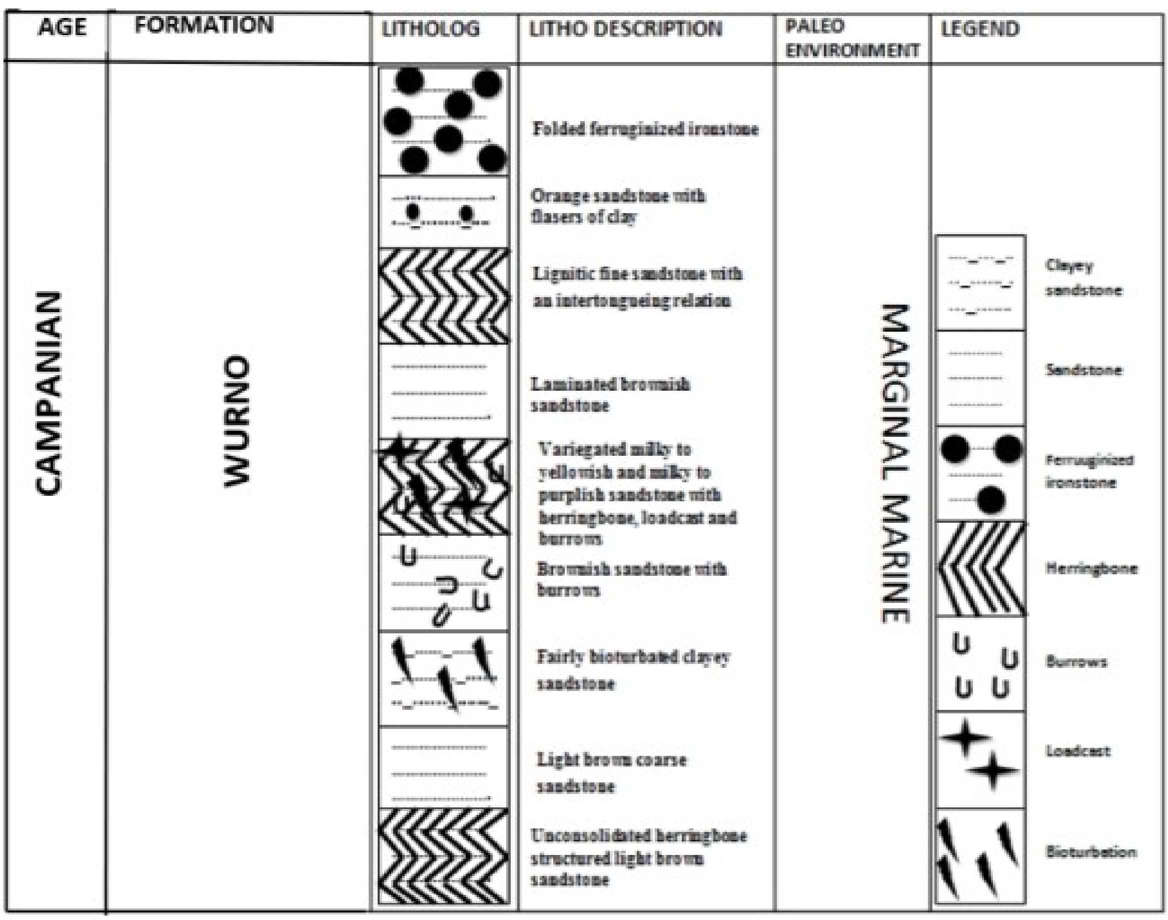

Fig. 1. Litholog of Runjin Beau outcrop

Plate 1. Bioturbation structure in Runjin Beau outcrop

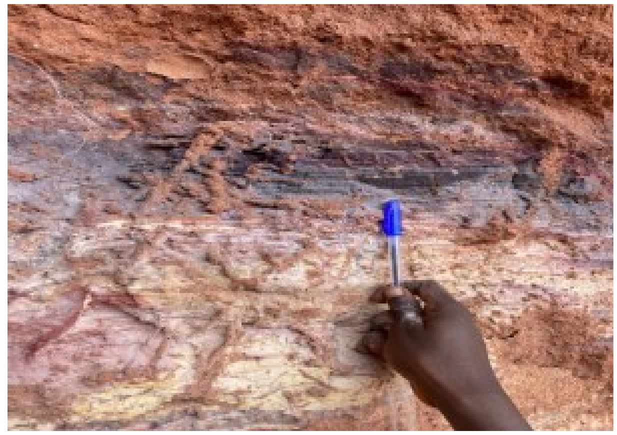

Plate 2. Vertical, Inclined and horizontal burrows

Plate 3. Fold and loadcast structures in Runjin Beau outcrop

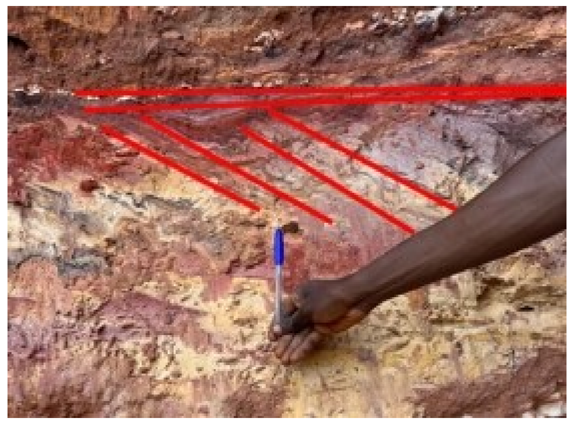

Plate 4. Herringbone Structure in Runjin Beau outcrop

Plate 5. Joint and inclined lobe structures in Runjin Beau outcrop

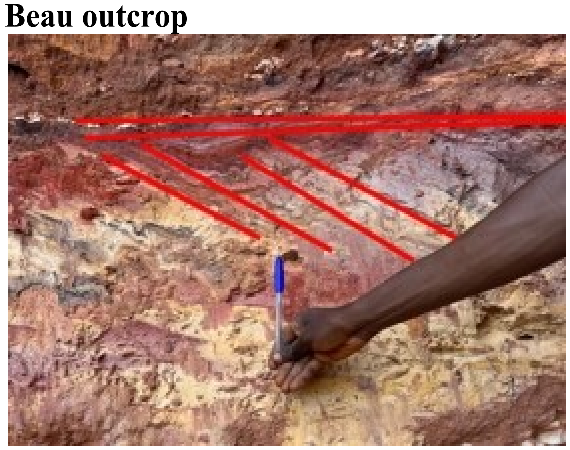

Plate 6 Angular unconformity in Runjin Beau outcrop

Table 1. Raw weight of samples obtained from sieving

Sieve (mm)	Phi Ø	5RU2 T	5RU2 M3	5RU2 M2	5RU2 M1	5RU2 B
2.00	-1.0	0.25	0.15	0.20	1.50	0.36
1.18	-0.25	0.80	0.90	0.87	5.02	0.69
0.85	0.25	1.96	1.94	1.95	6.59	1.84
0.60	0.75	2.72	2.96	2.92	7.30	2.92
0.425	1.25	7.70	7.46	7.50	20.50	7.60
0.30	1.75	15.02	15.30	14.60	25.13	15.00
0.25	2.0	25.02	25.22	25.44	10.92	25.12
0.15	2.75	40.23	40.03	40.21	15.48	40.13
0.10	3.25	3.60	3.20	3.28	2.62	3.40
0.075	3.75	0.35	0.45	0.45	1.65	0.55
0.063	4.0	1.65	1.53	1.54	2.93	1.63
Pan	5.0	0.80	0.92	0.92	0.30	0.82
Total		100.10	100.06	99.88	99.94	100.06

Table 2. Cumulative weight of the analyzed samples

e	Wt. of Sample SRU2 T	Wt. of Sample SRU2 M3	Wt. of Sample SRU2 M2	Wt. of Sample SRU2 M1	Wt. of Sample SRU2 B
-1.0	0.25	0.15	0.20	1.50	0.36
-0.25	1.05	1.05	1.07	6.52	1.05
0.25	3.01	2.99	3.02	13.11	2.89
0.75	5.73	5.95	5.94	20.41	5.81
1.25	13.43	13.41	13.44	40.91	13.41
1.75	28.45	28.71	28.04	66.04	28.41
2.0	53.47	53.93	53.48	76.96	53.53
2.75	93.70	93.96	93.69	92.44	93.66
3.25	97.30	97.16	96.97	95.06	97.06
3.75	97.65	97.61	97.42	96.71	97.61
4.0	99.30	99.14	98.96	99.64	99.24
5.0	100.10	100.06	99.88	99.94	100.06

Statistical data generated from the grain size parameters and their respective interpretations were presented in Table 3. The mean values obtained from logarithmic scale of cumulative frequency curves in Figs. 1, 3, 5, 7, and 9 were deduced after the work of Folk and Wards (1957). The mean values range between 1.37 and 2.13 with an average of 1.85, indicative of medium grain in size, with the exception of Sample SRU2 T (2.13), which is fine grain in size. The mean values obtained from the sediments suggest that the Runjin Beau Sandstone Member of the Wurno Formation has a grain size range from fine sand to medium. The variation in size was a response to the energy of transportation, rate of deposition and progressive landward deposition of the sediments, with the medium grain particles transported by high tide current characterized by ebb and flood currents, where sediment particles were carried and deposited beyond the beach dunes. The sediment particles are found to be associated with bi-directional cross beddings known as herringbone structures (Nwajide, 1980; Ladipo, 1988; Plt. 4).

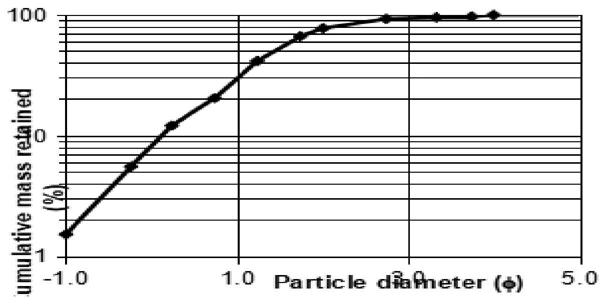

Fig. 2. Cumulative curve for Sample SRU2

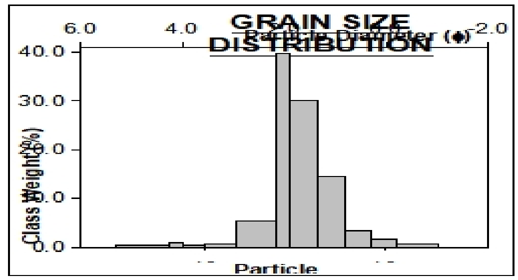

Fig. 3. Histogram of grain size distribution, Sample SRU2 T

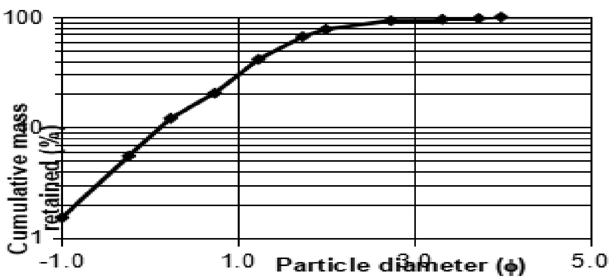

Fig. 6. Cumulative curve for Sample SRU2 M2

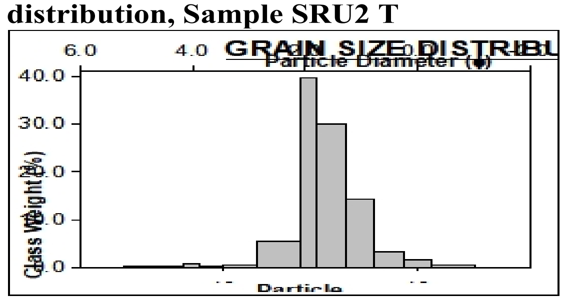

Fig. 7. Histogram of grain size distribution, Sample SRU2 M2

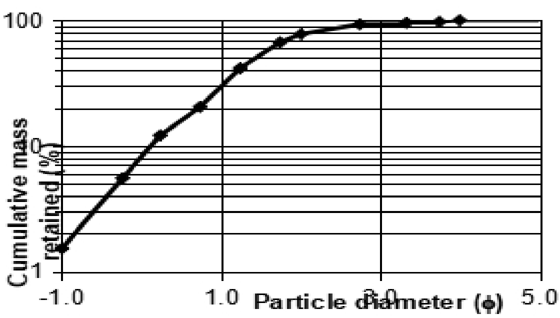

Fig. 8. Cumulative curve for Sample SRU2 M1

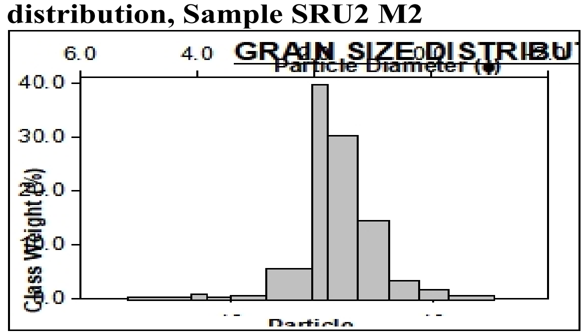

Fig. 9. Histogram of grain size distribution, Sample SRU2 M1

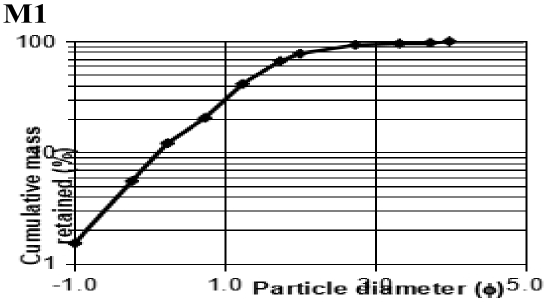

Fig. 10. Cumulative curve for Sample SRU2 B

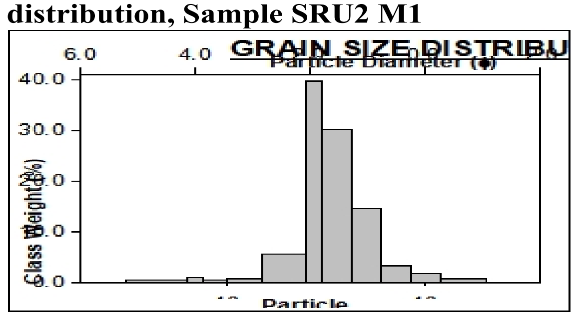

Fig. 11. Histogram of grain size distribution, Sample SRU2 B

Table 3. Summary of statistical grain size parameters and their interpretation

Sample Name	Mean Value	Mean Interpre Tation	Sorting Value	Sorting Interpre Tation	Skewness Value	Skewness Interpre tation	Kurtosis Value	Kurtosis Interpre tation
SRU2 T	2.13	Fine Sand	0.55	Moderately Well Sorted	0.14	Positively Skewed	1.6	Very Leptokurtic
SRU2 M3	1.93	Medium Sand	0.66	Moderately Well Sorted	-0.179	Negatively Skewed	1.2	Leptokurtic
SRU2 M2	1.9	Medium Sand	0.71	Moderately Well Sorted	-0.22	Negatively Skewed	1.23	Leptokurtic
SRU2 M1	1.37	Medium Sand	1.035	Moderately Sorted	-0.04	Nearly Symmetrical	1.52	Very Leptokurtic
SRU2 B	1.9	Medium Sand	0.65	Moderately Well Sorted	-0.07	Nearly Symmetrical	1.18	Leptokurtic

The Runjin Beau Sandstone Member in the Wurno Formation is loosely consolidated, fairly bioturbated and easily destroyed by rain or human activities. The textural and structural feature exhibited by the Wurno Sandstone facies are comparable to those of Ajali Sandstone in Anambara Basin (Nwajide, 1980; Ladipo, 1988), similar to Fugar Sandstone in Bida Basin (Adeigbe *et al.,* 2014), and it is also conveniently comparable with Dukku Sandstone in Gwandu Formation in Sokoto Basin, Nigeria (Ola-Buraimo *et al.,* 2022). The finer-grain particles of Sample SRU2 T are suggested to have been transported landward by a greater tidal magnitude, further away from the shoreline.

The current energy of deposition was mostly controlled by multiple currents, which permitted winnowing of the finer grains from the coarser materials. They are characterized by cross lamination in which they are suggested to be beach deposit, angularly deposited to the shoreline (Plt. 6). The sorting behaviors show that the standard deviation values range from 0.55 – 1.035 with an average value of 0.72. The sorting data obtained shows that all the samples belong to the moderately well sorted class except Sample SRU2 M1 which belongs to moderately sorted class. The moderately well sorted samples had a relatively high tidal magnitude and relatively higher winnowing effect, deposited landward in an intertidal to tidal zone setting. Landward shift in sedimentation was characterized by moderately sorted Sample SRU2 M1. This was transported and deposited by relatively greater and higher tidal magnitude, and little effect of winnowing, in an intertidal zone. The results obtained are similar to the work of Lawal and Yamusa (2025), but they interpreted a tidal flat setting, which is unlikely because the facies is not a clayey sandstone.

Skewness values for Runjin Beau Sandstone range from -0.22 to 0.14 with an average value of -0.074. The Skewness for the samples is categorized into three on the basis of their different values, such as positively skewed, negatively skewed and nearly symmetrically skewed. The positively skewed category belongs to Sample SRU2 T with a value of 0.14. It is described to have more fine grains in its assemblage than coarse materials. Such sediment was transported by relatively low energy and possibly slow rate of sedimentation. Another class of Skewness is the negatively skewed sediments of Samples SRU2 M3 and SRU2 M2, with values -0.179 and -0.22 with an average value -0.1995. The transportation mechanism is suggested to be by saltation for the coarse particles, while the finer particles were carried in suspension. This indicates a relatively higher energy of transportation than the positively skewed sediments. The last category of the skewness is the nearly symmetrically skewed of Samples SRU2 M1 and SRU2 B with values -0.07 and -0.04, respectively. Here, the transportation history suggests that there was an equal distribution of sediment particle sizes of both coarse and fine. The Kurtosis values 1.18-1.2 with an average value of 1.19 in Samples SRU2 M3, SRU2 M2 and SRU2 B belong to the leptokurtic class, while Samples SRU2 T and SRU2 M1 with values 1.52 and – 1.6 respectively belong to very leptokurtic class. The leptokurtic and very leptokurtic suggest bimodal sources of sediments.

3.3 Paleoenvironment of deposition

Paleoenvironment of deposition of the analyzed samples was determined based partly on the established fact that sorting values play an important role in determining whether a sediment assemblage belongs to either continental or beach (marine) through cross-examination of the mean, sorting and skewness (Ola-Buraimo *et al*., 2022). Sorting values less than 0.9 were described to be deposited in a beach environment, while sorting values greater than 0.9 were defined to have been deposited in a fluviatile setting (Friedman, 1967; Folk, 1980; Adeigbe *et al*., 2014; Oladimeji and Ola-Buraimo, 2022b; Ola-Buraimo *et al*., 2022). Paleoenvironment variables were presented in Table 4.4 with their corresponding depositional environments, modified after Friedman (1967). The sorting values of the analyzed samples vary from 0.55 to 1.035. Therefore, the sediments were deposited in a marginal marine and a typical marine paleoenvironment within a neritic setting. This was determined by plotting cross plots of Mean against Sorting and Skewness against Sorting as presented in Figs. 12 and 13. Four Samples out of the five Samples plotted within the beach environment, except Sample SRU2 M1, which was deposited in the fluvial environment of an intertidal setting (Figs. 12 and 13).

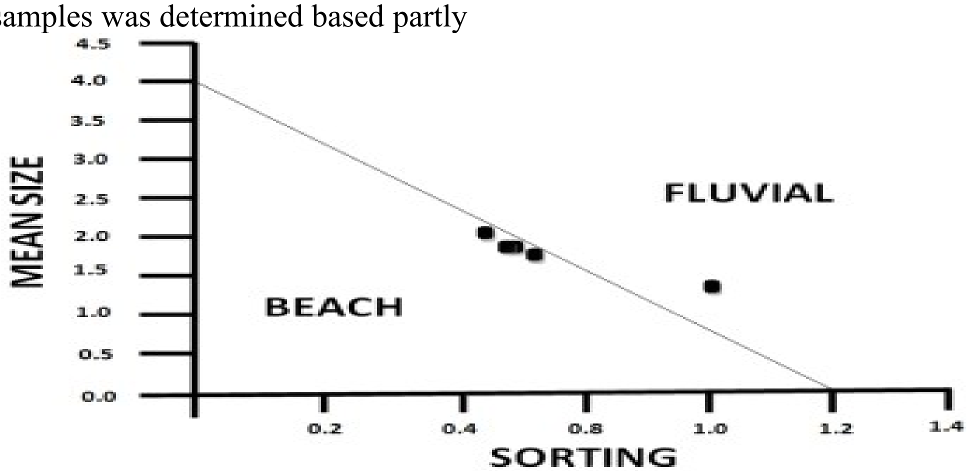

Fig. 12 Bivariate plots of Mean Size against Sorting

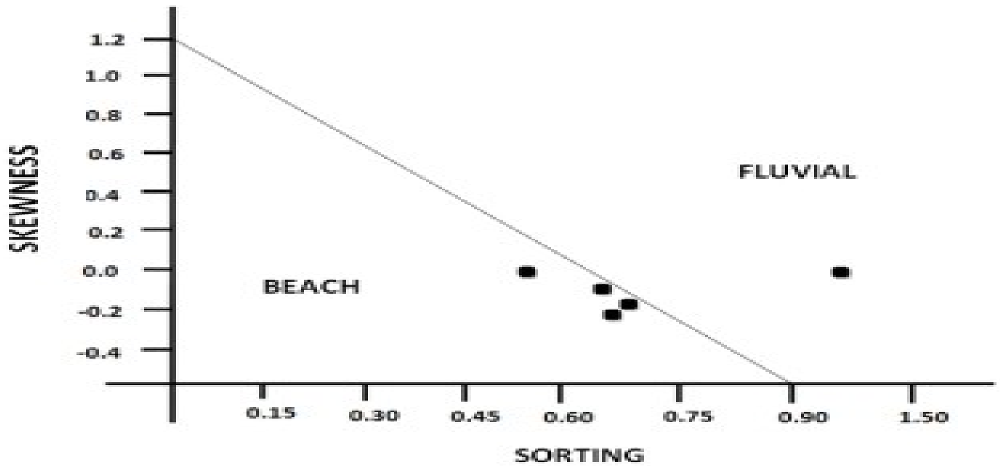

Fig. 13 Bivariate plots of slewness against sorting

The paleoenvironment of deposition of Runjin Beau Sandstone Member of the Wurno Formation was deduced by calculating multivariate values for the sediments of samples 1-5 in accordance to Sahu (1964) using a equation 1

$$MV = 0.2852\text{Mz} - 8.76045 - 4.8932SK\text{I} + 0.0482\text{KG} \quad (1)$$

where Mz = Grain size value, SKI = Skewness value, KG = Kurtosis value/

The results obtained from the calculation of the multivariate values for the analyzed samples are presented in Table 4.

The Multivariate values < -7.36 are intertidal, while values > -7.36 were deposited in tidal zone of the marginal marine system. This is similar to Fugar Sandstone (Adeigbe *et al*., 2014) and Dukku Sandstone in Gwandu Formation, Sokoto Basin, Nigeria (Ola-Buraimo *et al.,* 2022).

3.5 Heavy mineral

The result obtained from the heavy minerals analyzed under the microscope with their respective quantity is given in Table 5.

Heavy mineral result is presented in Table 5. The analyzed mineral assemblage suit shows that the heavy mineral assemblage includes zircon, rutile, tourmaline, other non-opaque minerals such as epidote, apatite, garnet, staurolite and opaque minerals (Mange and Maurer, 1992). There is no particular trend in the point count of the key heavy minerals such as zircon, tourmaline and rutile. However, zircon has the highest mineral count between 8-14 with an average count of 11. It is a non-silicate mineral occurring as an accessory constituent of felsic igneous rocks such as granite and metamorphic facies, such as gneiss and detrital deposits (Gujar & Rajamanickam, 2007).

Table 4. Multivariate values for the paleoenvironment of deposition

Sample name	Grain size (Mz)	Skewness (SKI	Kurtosis (KG)	Multivariate value (MV)	Depositional Setting	Depositional System
SRU2 T	2.13	0.14	1.6	-8.76	Intertidal	
SRU2 M3	1.93	-0.179	1.2	-7.28	Tidal shelf	
SRU2 M2	1.9	-0.22	1.23	-7.08	Tidal shelf	
SRU2 M1	1.37	-0.04	1.52	-8.10	Intertidal	Marginal marine
SRU2 B	1.9	-0.07	1.18	-7.82	Intertidal	

Table 5. Heavy mineral separation count

Sample No.	Zircon (Z)	Tourma-line (T)	Rutile (R)	Epidote (Ep)	Apatite (Ap)	Garnet (G)	Staurolite (St)	Opaque (Op)	ZTR Index (%)
5RU2 M1	11	9	10	3	3	4	15	75	54.5
5RU2 M2	12	9	9	3	3	8	13	86	52.6
5RU2 M3	10	8	14	3	3	6	13	80	56.1
5RU 2B	14	6	11	4	3	5	12	75	56.4
5RU 2T	8	10	8	5	4	7	13	79	47.3

Rutile appears second, next in abundance of the mineral suite recovered from the sediment samples. It ranges in abundance count from 8-14, with an average count of 10.4. It occurs commonly as an accessory mineral in igneous rock and many granites, diorites, and metamorphic derivatives such as gneisses and amphibolite, including other grades of metamorphism such as mica schist and high-grade metamorphism.

Tourmaline ranked third as the most abundant mineral, ranging from 6-10 with an average count of 8.4. It is usually formed during the hydrothermal activity of metamorphic rocks. It occurs in granitic pegmatite, schist, and commonly in detrital materials. The occurrences of zircon, rutile and tourmaline in the sediments indicate an acid igneous rock and metamorphic (bimodal) sources (Feo-codecido, 1956; Ola-Buraimo and Usman, 2022; Ola-Buraimo *et al*., 2022). However, mineralogy maturity was determined by adopting the composition maturity index after the work of Hubert (1962). This was based on the point count of zircon, tourmaline, rutile and other non-opaque heavy minerals; computed for each sample using the formula expressed in equation 2

$$ZTR\ index = \frac{Zircon+Tour+rutile}{Number\ of\ non\ opaque} \times \frac{100}{1} \qquad (2)$$

Therefore, calculated percentage of the determinant heavy minerals such as the zircon, tourmaline, and rutile were calculated and tabulated in Table 4.5 above. The ZTR Indices for the samples are generally moderate, ranging from 47.3 – 56.4 with an average value of 53.38. A relatively moderate ZTR index recorded for the samples suggests submature sediments that had been transported far away from the parent source rocks, but were affected by intermittent discharge of current energy, indicative of a marginal marine environment. Inferences from the ZTR Indices suggest mineralogical and possibly texturally submature sediments. ZTR Index less than 50 % is classified as immature (Hubert, 1964), ZTR less than 76 % is classified as sub-mature (Ola-Buraimo *et al*., 2022), while ZTR Index greater than 76 % is considered to be mature sediments.

Figure 14 shows a graphical expression in bar chart of ZTR Index for Samples 1-5. The Samples 1- 5 are suggested to have been transported by water currents, and the sediments were carried from the fluviatile environment under low current energy of transportation, deposited in a marine environment but subsequently subjected to the effect of tidal influence, where coarse materials were intermittently mixed with dominant fine-grained particles during the high tide. Therefore, the transportation and deposition processes did not give enough room for the sediments to achieve mineralogical maturity.

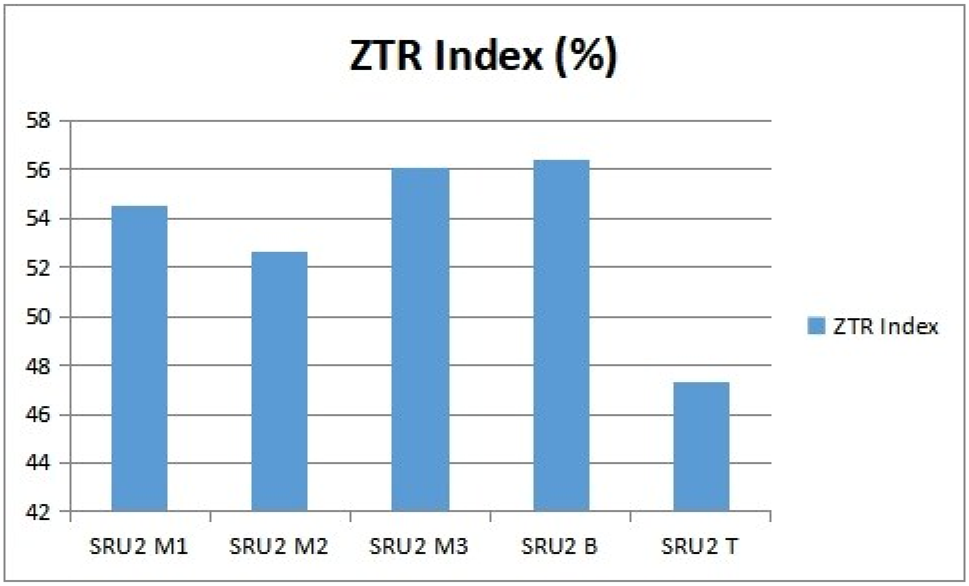

Fig. 14 Graphical representation of ZTR Index for Samples 1-5

3.6 Petrographic analysis

3.6.1 Mineralogical maturity

Mineralogical maturity index (MMI) of the sandstone samples is contained in Table 6. This was obtained by petrographic point count of quartz, feldspar and rock fragments. The mineralogical composition of the samples SRU2 T, SRU2 M3, SRU2 M2, SRU2 M1 and SRU2 B is dominated by quartz, representing 75 – 97 % with an average of 89.6 %, feldspars 0 %, and rock fragments 3 – 15 % with an average of 8.4 % (Plts. 4.12 – 4.16). MMI index was calculated using the formular advanced by Nwajide and Hoque (1985) using the parameters in Table 6. The mineralogical maturity index is determined using the expression

$$MMI = \frac{Proportion\ of\ quartz}{proportion\ of\ fsp + proportion\ of\ R.F} \quad (3)$$

Table 6. Composition of sandstone facies studied and the mineralogical maturity index

SAMPLE ID	Quartz (Qtz)	Feldspar (Fsp)	Rock (lithic fragment (RF)	Fsp+Rf	% Qtz	% Fsp+Rf	Mineralogical maturity index (MMI)
SRU2 T	92	0	8	8	92	8	11.5
SRU2 M3	89	0	11	11	89	11	8.1
SRU2 M2	95	0	5	5	95	5	19
SRU2 M1	75	0	15	15	75	15	5
SRU2 B	97	0	3	3	97	3	32.7
AVERAGE	89.6	0	8.4	8.4	89.8	8.4	15.3

The MMI index ranges from 5.0 to 32.7 with an average of 15.3 (Table 7). This suggested that the sediments are mineralogically submature to mature.

Sandstone Classification

A ternary diagram of quartz, feldspar and rock fragment plot shows that samples SRU2 T, SRU2 M1, SRU2 B are Quartz arenite with > 94 quartz, while samples SRU2 M2 and SRU2 M3 are Sublitharenite composed of <95 quartz with the matrix being rock fragments exceeding the percentage of feldspar (Folk, 1954; Fig. 15).

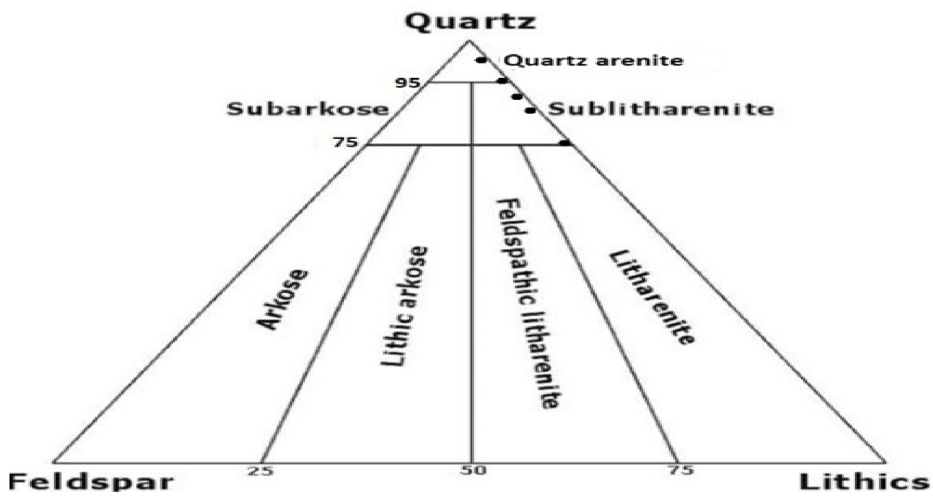

Fig. 15. Ternary diagram of Wurno Sandstone sediment classification

3.6.2 Textural maturity

Petrographic study was adopted to give an insight of the grain size, shape (angularity/ roundness) and sorting. The results obtained show that all the samples SRU2 T, SRU2 M3, SRU2 M2, SRU2 M1 and SRU2 B are medium grain sands (Table 7; Plates 12 – 16). Their shapes range from subrounded in Samples SRU2 T, SRU2 M3 and SRU2 M2 (Tab. 7; Plates 14-16), and rounded in Samples SRU2 M1 and SRU2 B (Tab. 7; Plts. 12 and 13). The petrographic view shows that all the Samples SRU2 T, SRU2 M3, SRU2 M2, SRU2 M1 and SRU2 B are moderately sorted (Tab. 4.7; Plts. 12-16). These results indicate that the sandstone samples vary from texturally mature to submature sandstones. Microphotographs of Samples 1-5 indicating grain size, shape and sorting under the microscope (Plts. 12-16).

Table 7. Textural maturity of the five samples from a petrographic view

S/NO	Name	Grain size	Grain shape(angularity/roundness)	Sorting
1	**SRU2 T**	Medium sand	Subrounded	Moderately sorted
2	**SRU2 M3**	Medium sand	Subrounded	Moderately sorted
3	**SRU2 M2**	Medium sand	Subrounded	Moderately sorted
4	**SRU2 M1**	Medium sand	Rounded	Moderately sorted
5	**SRU2 B**	Medium sand	Rounded	Moderately sorted

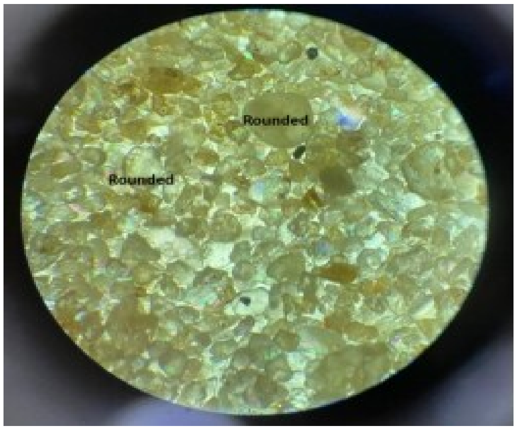

Plate 12 Microphotograph of SRU2 B XPL (mag. X40)

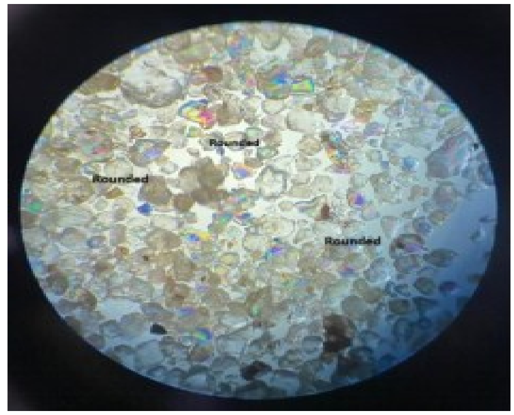

Plate 13 Microphotograph of SRU2 M1 XPL (Mag. X40)

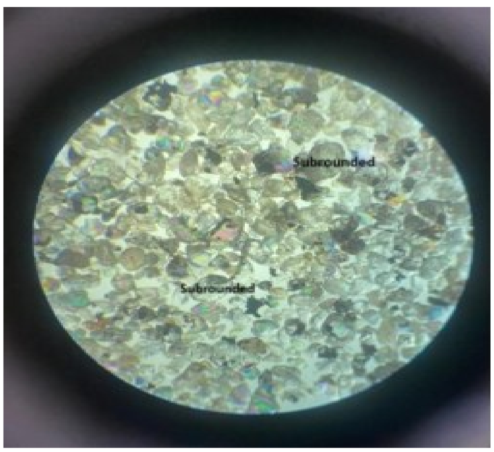

Plate 14 Microphotograph of SRU2 M2 XPL (Mag. X40)

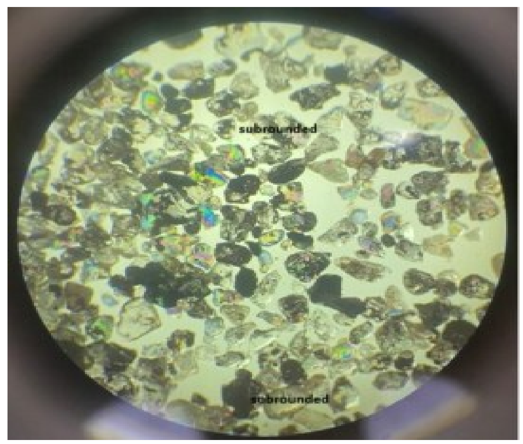

Plate 15 Microphotograph of SRU2 M3 XPL (Mag. X40)

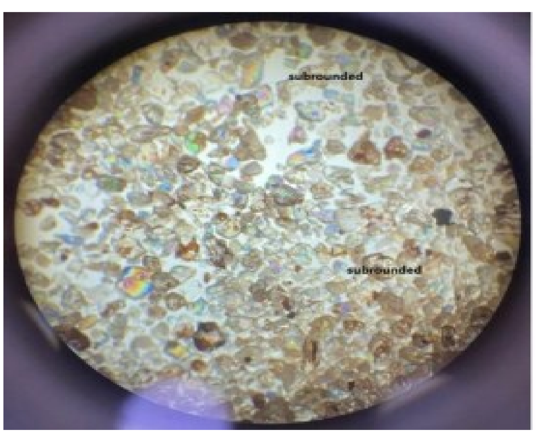

Plate 16. Microphotograph of SRU2 T XPL (Mag. X40}

4.0 Conclusion

Lithostratigrapahic sequence of the Wurno Formation is characterized by various lithofacies succession which include herringbone structure, unconsolidated medium sandstone, coarser light brownish sandstone, and clayey sandstone. This layer is overlain by variegated friable sandstone and brownish laminated sandstone. Gradational contact separates the laminated brownish sandstone from the overlying lignitic sandstone of a foreshore deposit, overlain by orange sandstone with clay flasers, overlain unconformably by angular laminated lignitic fine, orange sandstone of a washover channel, and at the top is folded ferruginized ironstone.

Grain size of the samples was classified into fine to medium grain-size-sediments. The sorting parameter ranges from moderately well sorted to moderately sorted. The skewness varies from nearly symmetrical to negatively skewed to positively skewed. The Kurtosis are both leptokurtic and very leptokurtic of biimodal sources. Bivariate plots indicate beach deposits except sample SRU2 M2, which was plotted in the fluvial segment. The multivariate index is indicative of intertidal to tidal shelf depositional environments, while the ZTR indices vary and are indicative of mineralogical submature sediments. Modal count of quartz, feldspar and rock fragments is indicative of quartz arenite, texturally matured and sublitharenite, texturally submatured sandstones.

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Declaration

Conflict of interest

No conflict of interest declared by the authors.

Availability of Data

Data shall be made available upon request.

Ethical Consideration

Not applicable

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Availability of Data

Data shall be made available upon request

Author Contributions

Ola-Buraimo A. Olatunji conceived and designed the study, conducted fieldwork, supervised granulometric, heavy mineral and petrographic analyses, interpreted the data, and drafted the manuscript. Musa A. Sadique carried out laboratory analyses, assisted with data processing and statistical interpretation, and contributed to results discussion and manuscript revision. Both authors approved the final manuscript.