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Sedimentological Characteristics of Ilaro Formation, Exposed Around Ajegunle, Dahomey Basin, Southwestern Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This study investigates the sandstones of the Ilaro Formation exposed in the Ajegunle area to infer their provenance, sedimentary history, and tectonic setting. Eleven samples were subjected to granulometric, petrographic, and heavy mineral analyses. Granulometric analysis, conducted in accordance with ASTM C136 standards, indicates that the sandstone sediments are medium to coarse-grained, poorly sorted, and exhibit nearly symmetrical to fine-skewed distributions with

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predominantly leptokurtic characteristics. The mean grain size of the sediments ranges from 1.30 mm to 0.65 mm, with an average of 0.98 mm, classifying them as arenaceous. The sediments also exhibit a significant argillaceous component, as indicated by the average skewness value of 0.11. Petrographic analysis identified quartz grains exhibiting polymodal fractures, along with the presence of opaque minerals and iron and clay as diagenetic cements. Heavy mineral analysis, using bromoform ($CHBr_3$), identified minerals such as tourmaline, rutile, zircon, staurolite, and opaque minerals, suggesting a mixed provenance from igneous and metamorphic source rocks. The results indicate that the Ajegunle Sandstone was deposited in a fluvial environment.

Keywords: Sedimentology; textural analysis; stratigraphy; provenance; ilaro formation-dahomey basin.

1. INTRODUCTION

Sandstones, a dominant category of siliciclastic sedimentary rocks, are important to understanding sedimentary processes and ancient depositional systems. These rocks form through the lithification of sand-sized detrital grains, often comprising quartz, feldspar, and lithic fragments, bound by cementing agents like silica, clay minerals, or iron oxides (Tucker, 2003). The textural and compositional characteristics of sandstones, including grain size, sorting, roundness, and mineral assemblages, serve as indicators for interpreting sediment provenance, depositional environments, and paleogeologic conditions (Boggs, 2009).

The Dahomey basin is a combination of inland / coastal / offshore basin within the Gulf of Guinea province (Obaje, 2009). The basin stretches from the southeastern Ghana through Togo and the Republic of Benin to southwestern Nigeria covering three different states, namely: Lagos, Ogun and Ondo. It is separated from the Niger Delta by a subsurface basement high referred to as the Okitipupa Ridge and Benin Hinge on the western flank of the Niger delta, (Jones and Hockey, 1964; Omatsola and Adegoke, 1981a). It is also bounded in the north by the Precambrian basement rock and the Bight of Benin in the south. Dahomey basin covers about 285 kilometers from Cotonou in Benin republic to the western flank of the Niger delta. This basin consists of sedimentary formation with age range of cretaceous to tertiary that outcrop in an arcuate belt roughly parallel to the ancient coastline. The tertiary sediments of the Dahomey basin thin out to the east and are partially cut off from the sediments of the Niger delta basin by the Okitipupa ridge (Olabode, 2006).

The sedimentary deposition in the basin follows an east west trend with about cretaceous strata thickness around 200m thick in the onshore area (Okosun, 1990). It is evident that some of the basement blocks underling the Dahomey embayment are displaced towards the NNE-SSW basin axis as well as towards the offshore. At base of the sedimentary succession is the bitumen bearing sand of enormous economic potentials. Shallow boreholes have penetrated continuous late cretaceous marine shales which correlated with Nkoporo shale formation. Nearer the coast and offshore, the marine beds are older. Lower tertiary marine unit (Paleocene Ewekoro limestone Formation and the Eocene phosphatic Oshosun formation) are exposed in quarries at Shagamu and Ewekoro and Ibese in Ogun state and at Onigbolo and Tabligbo in neighboring Benin republic. Detailed field work in the basin has allowed the recognition of sedimentary succession deposited in different deposition environments from the oldest to the youngest beginning with the cretaceous sequence of the Abeokuta group consisting of the Ise, Afowo and Araromi formation followed closely by the tertiary sequence which includes the Ewekoro, Akinbo, Oshosun, Ilaro and the coastal sand formations (Obaje, 2009).

Numerous studies have examined the stratigraphy, sedimentology, paleodepositional environments, biostratigraphy, and petroleum potential of most formations within the Dahomey Basin, some of which include Jones and Hockey, (1964); Omatsola and Adegoke (1981b); Akintola (2013); Fayose (1970); Enu (1985); Odunaike et al., (2010); Akinmosin et al., (2011); Haack et al., (2000); Coker (2002); Adekeye et al., (2005); Olabode (2006); Gebhardt et al., (2010), Jimoh et al., (2024). However, this study aims to establish baseline data on the sedimentological attributes of the Ilaro Formation, including grain size distribution, mineral composition, and depositional textures, to support future stratigraphic and sedimentary research in the Dahomey Basin.

The study employed granulometric analysis, heavy mineral and petrographic analysis to determine the mineral composition and the depositional environment of the Sandstone in the study area.

2. LOCATION, PHYSIOGRAPHY AND GEOLOGICAL FRAMEWORK OF THE STUDY AREA

The study area for this work is Ajegunle village along Papa-Alanto-Ilaro which is part of the eastern Dahomey basin at Ewekoro local government area of Ogun state, southwestern Nigeria. It is located on Latitude 6^0 53' 17"N and longitude 3^0 7'50" E with an elevation of 110 meters and the topography is typically characterized by low-lying areas and gentle slopes. The area was accessed by major roads. See Fig. 1 shows the geologic map of the study area.

3. METHODOLOGY

The methodologies utilized in this study involve two phases: fieldwork and laboratory analysis. The fieldwork phase involved the systematic collection of samples, detailed lithologic section logging, and the documentation of sedimentary features, including thickness, grain size, texture, color, and sedimentary structures observed within the study area. The laboratory analysis phase included granulometric analysis, heavy mineral analysis, and petrographic analysis, which provided a comprehensive evaluation of the collected samples.

3.1 Field Investigation

Lithological mapping and logging were conducted bed by bed from the base to the top of the exposed section, documenting sedimentary structures, textures, colors, and stratigraphic relations (See Fig. 2). Eleven fresh, unweathered samples were systematically collected using a hammer and chisel, with measurements taken and observations recorded. The section predominantly consists of sand grains with clay particles, displaying parallel lamination and cross-cutting beds. Paleocurrent analysis indicated a depositional flow direction of N20°E, consistent with shallow water conditions, while the claystone coloration suggested oxygenation and ferroginization. Samples were labeled AJ1a, AJ1b, AJ2a, AJ2b, AJ3a, AJ3b, AJ4, AJ5, AJ6, AJ7a, and AJ7b.

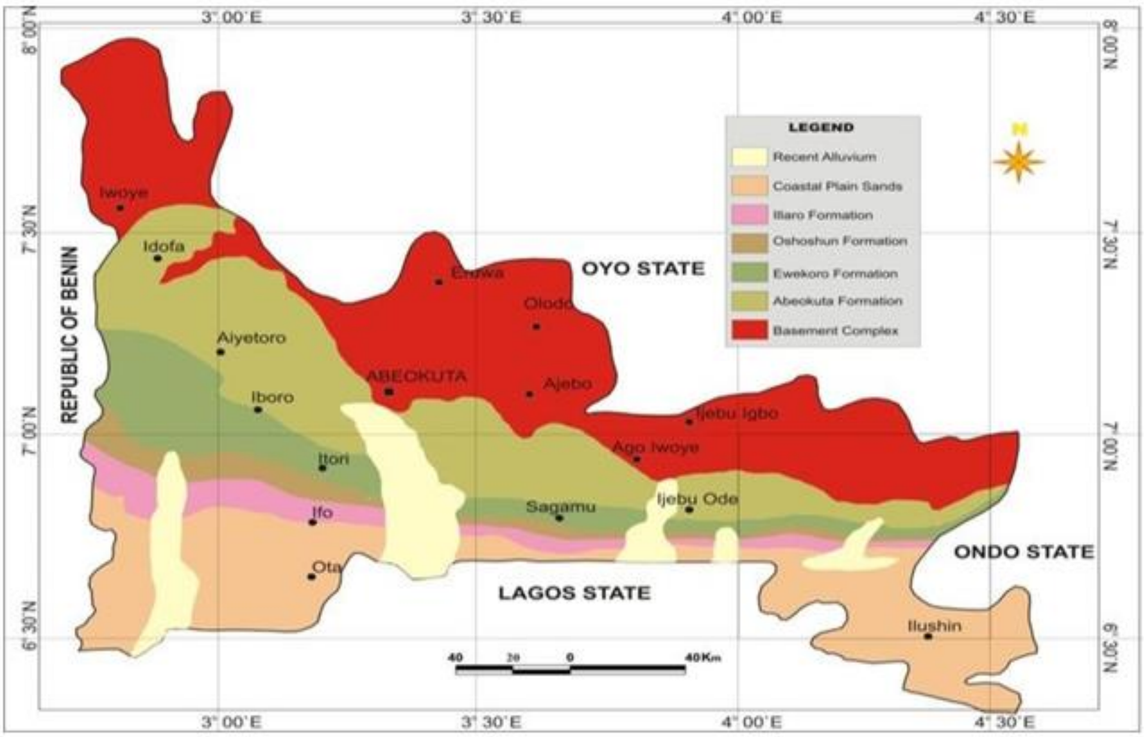

Fig. 1. Geological map of Ogun State showing the Ilaro Formation, modified from NGSA (2006)

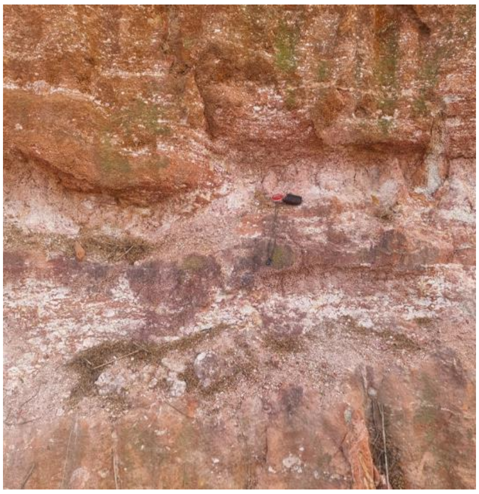

Fig. 2. Field Photograph of Sandstone Interbedded with Kaolinitic Clay Lenses in the Ilaro Formation, Ajegunle

3.2 Laboratory Analysis

The laboratory analysis encompassed granulometric, petrographic, and heavy mineral studies. Grain size distribution analysis was conducted on eleven sandstone samples to assess sorting, skewness, kurtosis, and graphic mean. Petrographic examination was performed on three samples (AJ1a, AJ3b, and AJ7a) using plane-polarized and cross-polarized light to identify rock-forming minerals, microstructures, and the mineralogical composition, as well as to evaluate the textural maturity of the mineral grains. Heavy mineral analysis was carried out on three selected samples (AJ1a, AJ3b and AJ7b) using the gravity method, employing Bromoform ($CHBr_3$) with a specific gravity of 2.89 for mineral separation. All laboratory analyses were conducted at the Sedimentological Laboratory, Department of Geology and Mineral Science at the University of Ilorin, Nigeria.

3.2.1 Sieve analysis

Granulometric analysis was conducted following the standard procedure outlined in ASTM C136. Approximately 100 grams of each dried sample were weighed using a digital scale and subjected to sieve analysis. A stack of sieves with mesh sizes ranging from 4.75 mm to 0.075 mm was used, arranged in descending order of mesh size. The sieve stack was placed in a mechanical shaker and vibrated for 15 minutes to ensure effective separation of particle sizes. The weight of material retained on each sieve was recorded, and the cumulative weight percentages were calculated. These data were used to determine the grain size distribution of the samples in accordance with Folk (1974).

- Graphic Mean [M]: Represents the average grain size.

$$\frac{\phi16+\phi50+\phi84}{3}$$

- Sorting (σ): Indicates the degree of uniformity in grain sizes, calculated as;

$$\frac{\phi84 - \phi16}{4} + \frac{\phi95 - \phi5}{6.6}$$

- Graphic Kurtosis [K] Reflects the peakedness of the grain size distribution, calculated as:

$$\frac{\phi95 - \phi5}{2.44(\phi75 - \phi25)}$$

- Graphic Skewness [SK]: Describes the symmetry of the grain size distribution, using the equation;

$$\frac{\phi16 + \phi84 - 2\phi50}{(\phi84 - \phi16)} + \frac{\phi5+ \phi95-2\phi50}{2(\phi95 - \phi5)}$$

3.2.2 Peterological analysis

The petrographic thin sections were prepared using a thin-section machine and examined under a microscope with a magnification of 20. The sandstones were classified in accordance with the standard Classification of Sandstone-according to Pettijohn, (1975). Mineralogical maturity and provenance were inferred based on the composition and texture of the samples.

3.2.3 Heavy minerals analysis

The fraction passing through the 250 µm sieve, representing the fine to medium sand fraction, was retained for heavy mineral separation. Although various liquids are available for the heavy liquid separation process, this study employed bromoform ($CHBr_3$), a high-density liquid with a specific gravity of 2.89 g/cm^3, to separate the heavy minerals from the lighter fractions effectively. Approximately 50 grams of the prepared sample was placed in a beaker. Bromoform was added to the sample to create a suspension, which was thoroughly stirred and allowed to settle for 5 minutes. The heavier mineral fraction settled at the bottom due to its higher specific gravity relative to bromoform. The heavy minerals were carefully separated using a pipette and transferred to a clean container.

The recovered heavy mineral fraction was air-dried, mounted on a glass slide, and examined under plane-polarized light (PPL) and cross-polarized light (XPL) using a polarized light microscope. Photomicrographs were captured to document the properties of the heavy minerals.

4. RESULTS AND DISCUSSION

4.1 Granulometric Analysis

The results of the phi (φ) data are summarized in Table 1, and the grain size analysis is summarized in Table 2. The grain size distribution, individual weights, cumulative weights, and cumulative weight percentages were calculated to generate histograms and cumulative frequency curves for each sample. Statistical parameters, including the phi values at the 5th, 16th, 25th, 50th, 75th, 84th, and 95th percentiles, were derived from the cumulative frequency curves.

The mean grain size of the sandstone sediments in the study area ranges from 1.30 mm (medium sand) to 0.65 mm (coarse sand), with an average of 0.98 mm, classifying the sediments as arenaceous with a notable argillaceous component. This classification is supported by an average skewness value of 0.11, indicating a fine-skewed distribution (Folk, 1974; Wentworth, 1922). The calculated sorting values range from 0.87 (moderately sorted) to 1.39 (poorly sorted), with an average value of 1.09 (poorly sorted). Poor sorting in sandstones is indicative of deposition in high-energy environments. According to Blatt et al. (1980), river sediments are typically poorly sorted, reflecting variability in current velocities during transport and deposition.

The poor sorting observed in the samples suggests that the sandstones are texturally immature, influenced by the composition of the matrix. Based on the results obtained, kurtosis values range from 1.01 (mesokurtic) to 1.99 (very leptokurtic), while skewness values range from -0.08 (nearly symmetrical) to 0.28 (fine-skewed) with an average of 0.11 (fine-skewed). River sands are generally moderately to poorly sorted and positively skewed, indicative of deposition in high-energy fluvial environments, whereas beach sands are well sorted and negatively skewed due to wave action (Friedman, 1961).

The scatter plots of mean grain size versus sorting, skewness versus kurtosis, and skewness versus sorting, as shown in Fig. 3, suggest that the sandstone facies were deposited in an alluvial environment.

4.2 Paleo Environment of Sandstone Facies

The relationship between granulometric parameters is important in interpreting the transport and depositional environments of sediments, as highlighted by previous studies (Adekeye et al., 2007; Ikhane et al., 2012). The bivariate plots generated from the analysis indicate that the samples predominantly plot within the beach and fluvial environments typical of littoral zones in coastal settings.

The results, as summarized in Table 2 and illustrated in the bivariate plots of mean grain size against sorting, Fig. 3, reveals that the sediments are generally poorly sorted, with sorting values ranging from 0.87 (moderately sorted) to 1.39 (poorly sorted) and an average of 1.09, consistent with poorly sorted coarse sandstones.

Table 1. phi (φ) data of samples AJ1a to AJ7b

Sample ID	φ5	φ16	φ25	φ50	φ75	φ84	φ95
AJ-1a	-0.60	0.10	0.32	0.83	1.40	1.70	2.50
AJ-1b	-0.40	0.20	0.45	1.10	1.75	2.10	2.80
AJ-2a	-0.90	0.00	0.30	1.00	1.58	1.90	2.70
AJ-2b	-0.50	0.20	0.40	0.90	1.75	2.20	2.90
AJ-3a	-0.80	0.30	0.81	0.93	1.60	2.10	3.05
AJ-3b	-1.20	-0.30	0.10	0.80	1.82	2.40	3.40
AJ-4	-0.70	0.10	0.35	1.00	1.62	2.00	2.80
AJ-5	-0.90	-0.10	0.20	0.60	1.30	1.80	3.35
AJ-6	-1.30	-0.35	0.05	0.59	1.25	1.70	2.85
AJ-7a	-1.55	-0.20	0.29	1.15	2.00	2.40	3.30
AJ-7b	-0.80	-0.10	0.20	0.75	1.45	1.85	3.30

Table 2. Results of the Mean, Sorting, Skewness, and Kurtosis with their respective Interpretation of the Analyzed samples

Sample Name	Mean Values	Interpretation of Mean Values	Sorting Values	Interpretation of Sorting Values	Skewness Values	Interpretation of Skewness Values	Kurtosis Values	Interpretation of Kurtosis Values
AJ1a	0.88	Coarse sand	0.87	Moderately sorted	0.08	Nearly symmetrical	1.18	Leptokurtic
AJ1b	1.30	Medium sand	0.96	Moderately sorted	0.06	Nearly symmetrical	1.01	Mesokurtic
AJ2a	0.97	Coarse sand	1.02	Poorly sorted	-0.05	Nearly symmetrical	1.15	Leptokurtic
AJ2b	1.10	Medium sand	1.02	Poorly sorted	0.24	Fine skewed	1.02	Mesokurtic
AJ3a	1.11	Medium sand	1.03	Poorly sorted	0.20	Fine skewed	1.99	Very Leptokurtic
AJ3b	0.97	Coarse sand	1.37	Poorly sorted	0.16	Fine skewed	1.10	Mesokurtic
AJ4	1.03	Medium sand	1.01	Poorly sorted	0.04	Nearly symmetrical	1.13	Leptokurtic
AJ5	0.77	Coarse sand	1.12	Poorly sorted	0.28	Fine skewed	1.58	Very Leptokurtic
AJ6	0.65	Coarse sand	1.14	Poorly sorted	0.09	Near symmetrical	1.42	Leptokurtic
AJ7a	1.12	Medium sand	1.39	Poorly sorted	-0.08	Nearly symmetrical	1.16	Leptokurtic
AJ7b	0.83	Coarse sand	1.11	Poorly sorted	0.19	Fine skewed	1.34	Leptokurtic

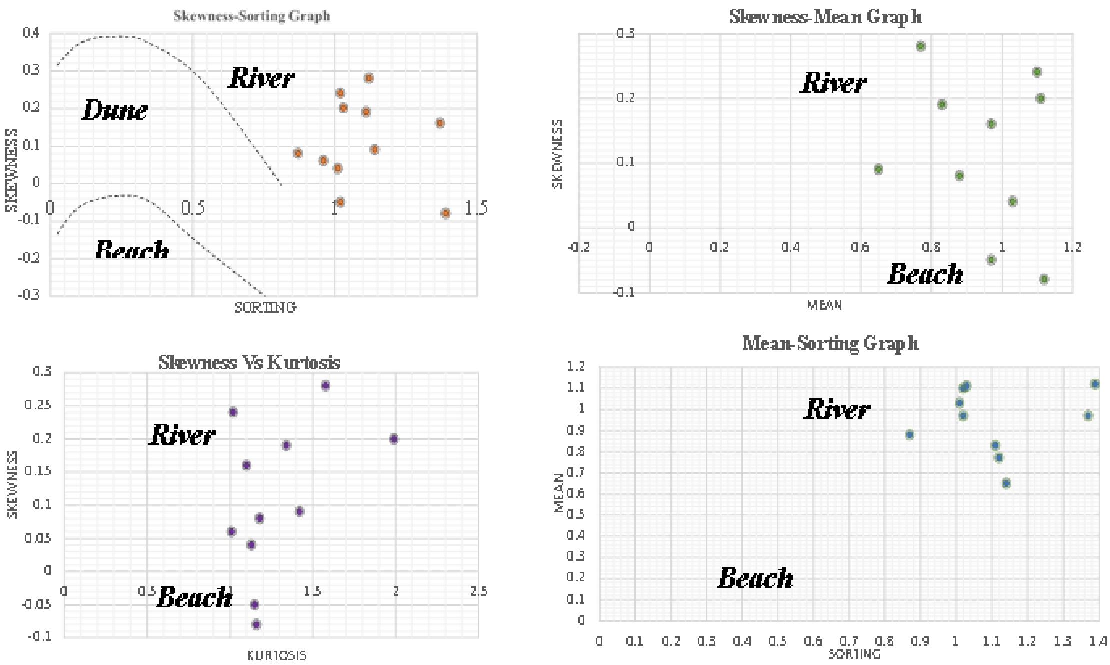

Fig. 3. Bivariate plots showing relationships between Mean, Sorting, Skewness, and Kurtosis

Further analysis using the bivariate plot of skewness versus kurtosis (Fig. 3) demonstrates a wide range of sediment characteristics, varying from nearly symmetrical to fine-skewed, with kurtosis values ranging from mesokurtic to very leptokurtic. These variations reflect diverse depositional processes.

Overall, the plotted points from the bivariate analyses suggest that the sediments were primarily deposited in a fluvial environment with minimal influence from beach processes.

4.3 Petrographic Analysis

The petrographic study was carried out on three samples: AJ1a, AJ3b, and AJ7a, using both plane-polarized light and cross-polarized light. Using a 20x magnification, the analysis reveals a dominance of quartz grains, with moderate amounts of feldspar and lithic fragments. Quartz crystals with internal fractures and evidence of iron (Fe) as a cementing material, along with the presence of plagioclase and minor mica, suggest a source area dominated by feldspar-rich crystalline rocks (Boggs, 2009). Sample AJ3b displays small quartz crystals (max. 4mm) banded by Fe minerals within a clay matrix, which has not been altered. Sample AJ1a consists primarily of quartz crystals (~95%), with polymodal fractures and less than 2% mica. According to Lambert (1979) and Martinelli et al. (2020), the presence of polymodal fractures in quartz grains reflects a history of mechanical stress during transport or multiple episodes of deformation, suggesting deposition in high-energy environments. Sample AJ7b is dominated by quartz crystals and feldspar (plagioclase), with evidence of some rock fragments. These samples suggest that the sandstones are texturally sub-mature, indicating they are relatively close to their source area. The quartz grains in the samples lack cleavage but exhibit uneven fractures, while the euhedral plagioclase crystals, which originated from the weathering of feldspar-rich crystalline rocks, suggest that the sandstones are mineralogically mature. Monocrystalline quartz grains, indicative of an igneous origin, and polycrystalline quartz grains, suggesting a metamorphic origin, were identified in samples AJ1a, AJ3b, and AJ7a (Figs. 4 –6). The sandstones are classified as sub-arkoses according to Folk et al. (1970), with quartz content ranging from 80% to 95% and a heterogeneous mixture of quartz, feldspar, and lithic fragments.

a) The photomicrograph of sandstone sample A1a viewed under plane polarized light and cross polarized light showing dominantly quartz crystals with internal fractures. The slide also shows evidence of iron (Fe) as the cementing materials in between grains.

b) The photomicrograph of sandstone sample AJ3b viewed under plane polarized light and cross polarized light showing small crystal quartz max 4mm banded by Fe minerals with clay matrix that has not been altered.
c) The photomicrograph of sandstone sample AJ7a viewed under plane polarized light and cross polarized light showing dominantly quartz crystals about 95% with polymodal fracture bounded by <2% mica and some opaque minerals.

4.4 Heavy Mineral Analysis

Three sandstone samples from the study area AJ1a, AJ3b, and AJ7b were subjected to heavy mineral analysis, and photomicrographs of the thin sections are presented in Figs. 7, 8, and 9. A detailed examination of the thin sections at 20x magnification revealed the presence of six distinct heavy minerals: zircon, rutile, tourmaline, tremolite, opaque minerals, and staurolite. These minerals were identified based on their optical properties, morphology, and distinguishing features under a petrographic microscope.

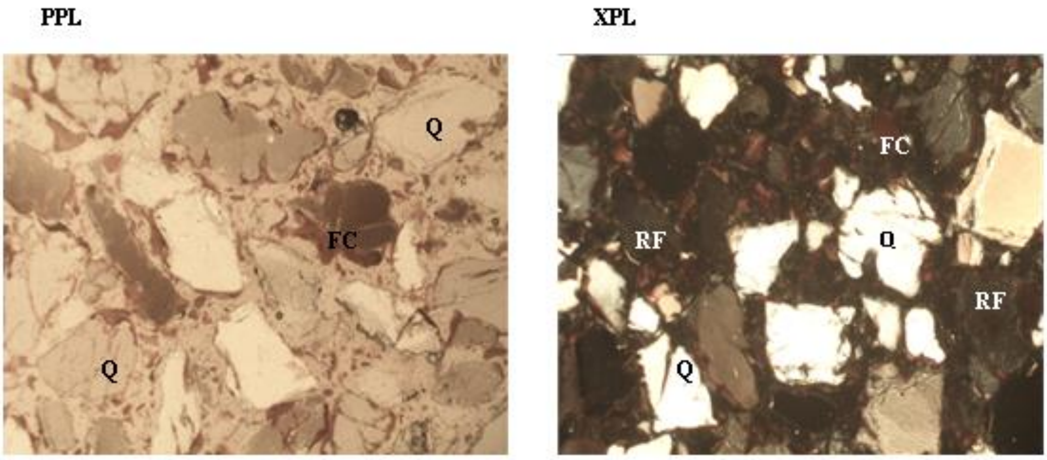

Fig. 4. Photomicrograph of sample AJ1a under plane and cross polarized light (Q= Quartz, RF= Rock Fragment & FC=Ferruginous Cement)

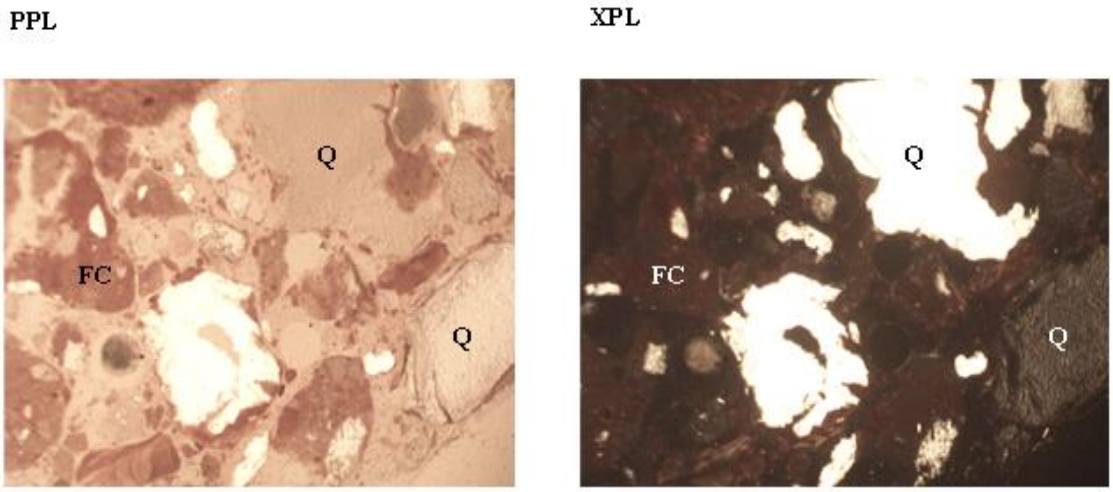

Fig. 5. Photomicrograph of sample AJ3b under plane and cross polarized light polarized (FC=Ferruginous Cement, Q= Quartz)

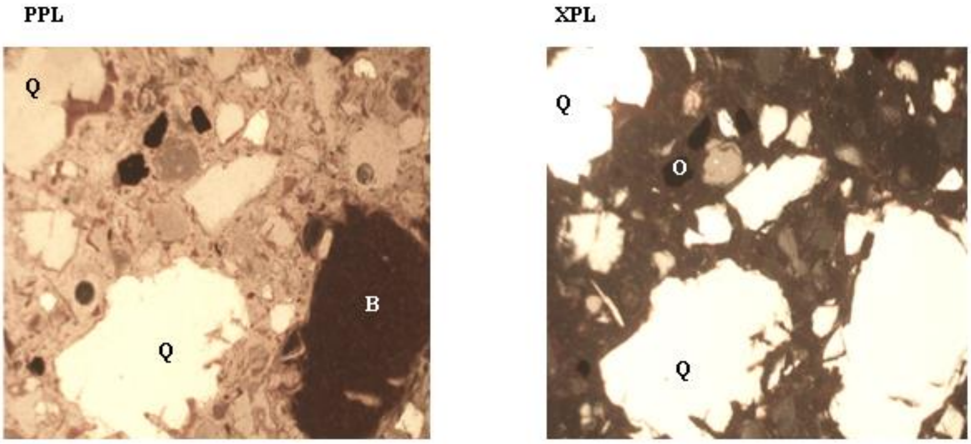

Fig. 6. Photomicrograph of sample AJ7a under plane and cross polarized light (O= Opaque Mineral, Q= Quartz)

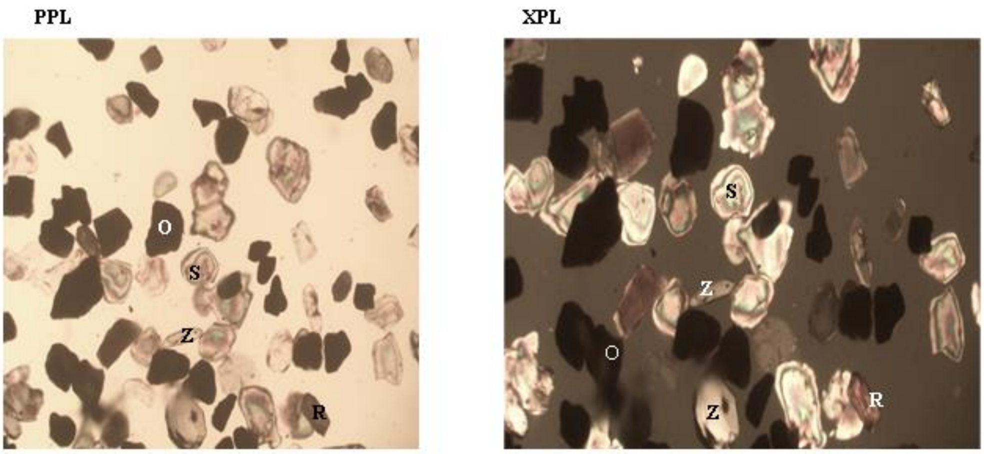

Fig. 7. Photomicrograph of sample AJ1a under plane and cross polarized light. (O= Opaque mineral, Z= Zircon, R= Rutile, S= Staurolite)

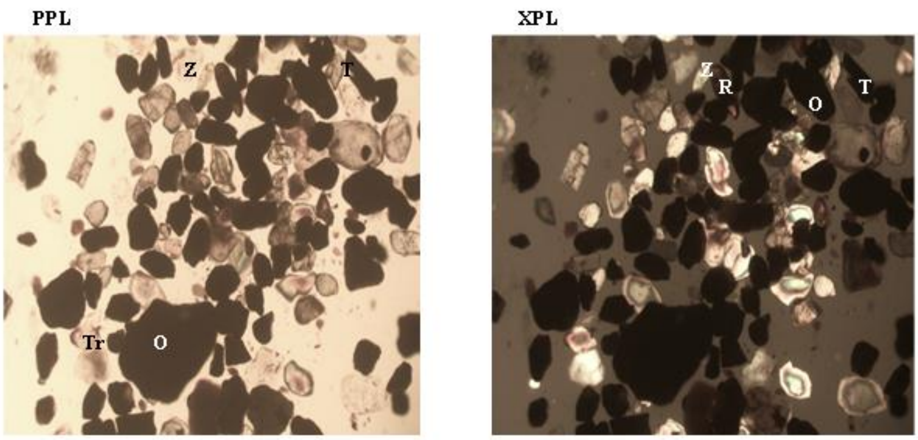

Fig. 8. Photomicrograph of AJ3b under plane and cross polarized light. (O= Opaque Mineral, Z= Zircon, R= Rutile, T= Tourmaline Tr= Tremolite)

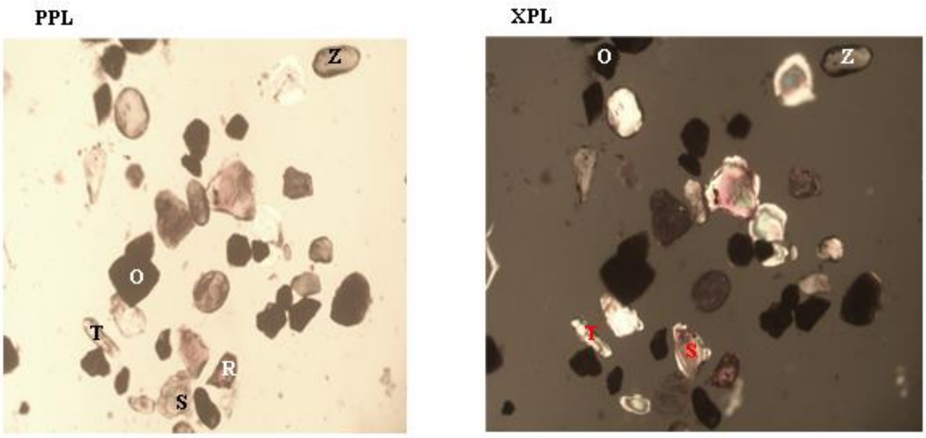

Fig. 9. Photomicrograph of sample AJ7b under plane and cross polarized light. (O= Opaque Mineral, Z= Zircon, T= Tourmaline, R= Rutile, S= Staurolite)

The heavy mineral assemblage, provides additional evidence of a heterogeneous provenance. The sediments were inferred to have originated from a mix of igneous and metamorphic rocks, such as pegmatites, schists, gneisses, and marble, with possible contributions from pneumatolytic environments due to the presence of tourmaline.

5. CONCLUSION

Based on the findings, grain size analysis of the sandstones indicates that the sandstone units in the studied area are coarse-grained, nearly symmetrical to fine-skewed, mesokurtic to very leptokurtic, and poorly sorted—characteristics indicative of a fluvial depositional setting. Petrographic analysis revealed that the sandstones are texturally sub-mature, suggesting proximity to the source area. The quartz grains exhibited uneven fractures, while the euhedral plagioclase crystals, inferred to have been derived from feldspar-rich rocks, suggest mineralogical maturity.

Samples AJ1a, AJ3b, and AJ7a revealed a mixture of monocrystalline quartz grains, indicative of an igneous provenance, and polycrystalline quartz grains, suggesting a metamorphic origin. The identification of six distinct heavy minerals zircon, rutile, tourmaline, tremolite, opaque minerals, and staurolite further supports a mixed provenance. These findings collectively suggest that the Ajegunle sandstones were deposited in a fluvial environment with contributions from both igneous and metamorphic source rocks.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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