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TEXTURAL AND PROVENANCE STUDIES OF AJALI SANDSTONES FORMATION OUTCROPPING IN IDAH, NORTHERN ANAMBRA BASIN, NIGERIA

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ABSTRACT

This study presents analytical evidence on the provenance and environment of deposition of the Maastrichtian Ajali Sandstone Formation outcropping in Idah based on its textural and petrographic characteristics. The aim is to evaluate its depositional mechanisms, paleoclimate, provenance, and depositional environment. Granulometric analysis and thin section petrography were carried out on sediment samples from outcrop sections along the western flank of River Niger. The granulometric studies reveal the dominance of coarse to medium-grained (0.62 to 1.54φ) and moderately to poorly sorted sandstone (0.88–1.20φ). The sandstones are strongly coarsely skewed with an average mesokurtic value of 1.03φ. Linear Discriminant Function (LDF) for environmental discrimination reveals a dominance of Beach and shallow agitated marine (subtidal) environments in Y1 and Y2. At the same time, Y3 indicates an interplay of shallow marine and fluvio-deltaic environments. Results indicate high dominance of quartz minerals (73%) and an absence of feldspar minerals, indicating high compositional maturity. These results suggest that the fluvio-deltaic sediments of the Ajali Sandstone in Idah were sourced from the northeast-trending Santonian Okigwe-Abakaliki anticlinorium and the Precambrian Cameroun Mountains.

Keywords: **Ajali Formation; Petrography; Paleo environment; Provenance**

1. Introduction

Clastic sedimentation is characterised by the interaction between physical, chemical, and biological processes of weathering, erosion, transportation and deposition that result in the formation of sediments and sedimentary environments (Chernicoff & Whitney, 2007; Nichols, 2009). As these processes are often preserved in the sedimentary record, using textural characteristics (Pettijohn et al., 1992) and mineral assemblages (Tucker, 1991) is essential in diagnosing provenance and sedimentary environments of clastic sediments. Characterising the provenance of clastic sediments is significant in reconstructing the origin of the sediments before the reworking process (Potter et al., 2005; Boggs, 2006; Alege et al., 2020).

Due to its superior aquifer and reservoir qualities, the siliciclastic Maastritchtian Ajali Sandstone Formation, the subject of this research, is a significant lithostratigraphic unit of the Anambra Basin, SE Nigeria. Numerous writers have researched this sedimentary unit, inferring its origin and the depositional environment from its textural features and petrographic properties. Tijani et al. (2010), inferred the provenance and weathering conditions of the formation by examining its textural, mineralogical and geochemical characteristics. Ilevbare and Omodolor (2020), studied the sediments of the Ajali Formation in the western flank by using the textural characteristics and pebble morphometry to interpret its depositional environment. Similarly, (Hoque & Ezepue, 1977; Ladipo, 1988; Adamu et al., 2018; Tijani et al., 2010) and (Akpofure and Etu-Efeotor, 2013; Onyekuru et al., 2019; Ezike et al., 2020) have utilised grain size analysis, petrography and paleocurrent patterns to decipher the provenance and depositional environment of Ajali Sandstones.

Hence, the objectives of this study are to (1) generate new analytical data on the textural characteristics and petrography of the Maastrichtian Ajali Sandstones of Anambra Basin outcropping at Idah; and (2) Integrate petrographic and textural characteristics for determining the origin, paleodepositional processes, and environment. This is aimed at ascertaining the post-Santonian age of the Ajali Sandstones in a continental shelf environment.

2. Location of the Study area

One of Nigeria's seven sedimentary basins, the Anambra Basin has a surface area of around 40,000 km2 (Murat, 1972). It is situated in the southwest corner of the Benue Trough and has a genetic ancestry with the Benue Trough. The Precambrian Basement Complex rocks of western Nigeria form the western border of the basin. Its eastern border is defined by the Abakaliki Anticlinorium. According to Anakwuba et al. (2018) and Obi and Okogbue (2004), the Campanian-Maastrichtian marked the beginning of sediment deposition in the basin, which was followed by a short marine transgression and regression.

Sediments from the Cretaceous make up the basin (Fig. 1a). The Anambra Basin's sedimentation process began with the marine and paralic shales of the Campanian–Maastrichtian Nkporo Formations, later covered by the Mamu Formation Coal Measures. The underlying fluviodeltaic sandstones of the Ajali and Owelli Formations are the Mamu Formation's lateral counterparts (Idakwo et al., 2013). The Nkporo Shale and Ajali Sandstones were deposited on top of the Mamu Formation sediments, which were accumulated by the basin's gradual subsidence and initiated by a regression during the Maastrichtian. The false-bedded sandstones of the Ajali Formation are thick, friable, poorly sorted, and generally white with sporadic iron stains. In a large expanse west of the Udi Plateau, the Nsukka Formation conformably overlies the Ajali Sandstone (Reyment, 1965).

The research location is in Idah, on the western bank of the Niger River, within the Ajali Formation of the Anambra Basin. It lies between longitudes 07007'32" to 07007'33.9" north and latitudes 06044'17.0" to 06044'18.5" east (Fig. 1b). This region is accessible via undulating footpaths on the Ajegwu-Idah road and Ocheche River channels at an elevation of 30 metres, with the river trending

200 degrees to the north-northeast, which provides excellent and fresh exposures. The exposures can also be located along certain segments of the path. The streams have a linear pattern of drainage.

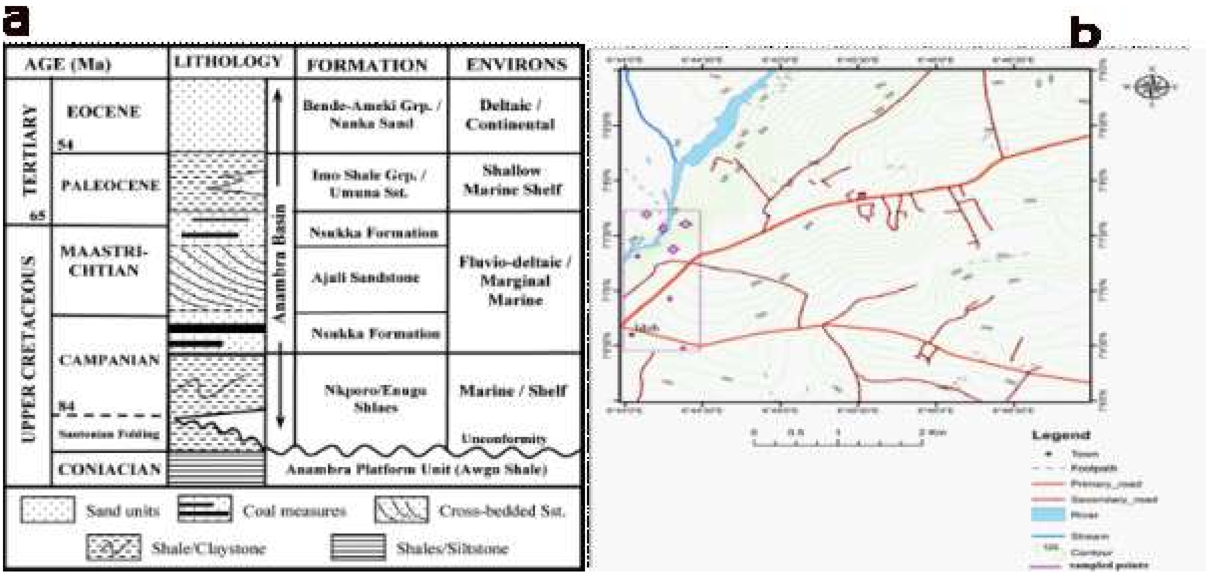

Figure 1 (a). Stratigraphic profiles and depositional environment of the sedimentary units within the Anambra Basin Nigeria (Tijani et al., 2010). (b) Location map showing the sampled points (purple) in the study area.

3. Materials and method

Seven sections of unconsolidated sandstones were collected from the study area at various locations (Fig. 1) after a comprehensive lithologic recording of various outcrop sections from bottom to top and designated as OR1, OR2, OR3, OR4, OR5, OR6, and OR7.

The samples were measured, sun-dried, and carefully disaggregated by hand for sieve analysis using the method described by Tucker (1996) for particle size distribution. Other grain-size parameters like mean sorting, skewness, and kurtosis were determined based on Folk and Ward's (1957) concept of statistical analysis of sediments.

The Linear Discriminate Function (LDF) method was employed to statistically analyse the variation of the energy of the environment of deposition. Sahu (1964) provided a statistical approach to discriminate depositional environments using multivariate analysis that compares discriminant functions of different environments (Yn) to an environmental mean, thereby determining the possible environments of comparable samples as given in the following equations:

$$Y1_{(A:B)} = 3.5688M + 3.7016\sigma_1^2 - 2.0766Sk_1 + 3.1135K_G \quad (1)$$

If $Y1 > -2.7411$, Beach is suggested, but if $Y < -2.7411$, Aeolian deposition is indicated.

$$Y2_{(B:SM)} = 15.6534M + 65.7091\sigma_1^2 + 18.1071Sk_1 + 18.5043K_G \quad (2)$$

If Y2 <63.3650, the environment is 'Beach (backshore)', but if Y2 >63.3650, the environment is 'Shallow agitated marine' (subtidal environment)

$$Y3_{(SM:F)} = 0.2852M - 8.7604\sigma_1^2 - 4.8932Sk_1 + 0.0482K_G \quad (3)$$

If Y3 >−7.4190, the environment is 'Shallow marine (SM)' (subtidal), but if Y3 <−7.4190, the environment is 'Fluvial deltaic (F).

In equations (1), (2) and (3), Mis the mean size, σ_1^2 is the variance, Sk_1 is the skewness, and K_G is the kurtosis. A, B, SM, and F represent aeolian, Beach, shallow marine and fluvial environments, respectively.

Thin sections from five sections were studied petrographically to determine the mineralogical composition. A homogenised and considerable quantity of each poorly consolidated sample was measured into an aluminium foil and mildly heated on a hot plate to desiccate the sample. The glass slides were then frosted to enhance a flat surface with uniform thickness and eliminate spots that could interfere with the result. Each frosted glass slide was heated, and appropriate Canada balsam was spread over it. The mildly heated unconsolidated sample was carefully impregnated into the Canada balsam on the glass slide and allowed to stabilise/ solidify for about 24 hours (Dickinson, 1970; Osae et al., 2006). The thickness of each impregnated rock sample was reduced by the lapping arm of a Hillquist machine and eventually by frosting using 600 grits and 800 grits carborundum. The minerals were carefully identified and observed using a petrographic microscope during frosting. The processes of frosting and observation continued until the desired thickness of 0.03 mm was reached, and the minerals were identified and observed(Ingersoll et al., 1984).

4. Results and interpretation

4.4. Granulometric Studies

The Ajali Formation exposed in the Idah area was mapped at seven (7) locations (OR1, OR2, OR3, OR4, OR5, OR6 and OR7) (Plate 1a, b, c, d, e, f, and g). Each section is a well-exposed sandstone with thicknesses ranging from 1m to 10m.

Plate A- D: Field photographs of measured sections of A, B, C and D representing outcrops OR1, OR2, OR3 and OR4, respectively, of Ajali Sandstone in the Idah area.

Plate E- G: Field photographs of measured sections of E, F and D representing outcrops OR5, OR6, and OR7 of Ajali Sandstone in the Idah area.

The samples were sieved, statistically characterised and presented in Table 1. The results of the mean size of the sediments show a medium (59.14 %) to coarse (42.86%) grained texture ranging from 0.62φ to 1.54φ. The measure of sorting of the sediments varies from moderately well sorted to poorly sorted, with an average value of 1.10φ indicative of poorly sorted sediment. The average degree of asymmetry of the grain size distribution is strongly coarse skewed, and the kurtosis value suggests platykurtic to leptokurtic, with most of the samples having a leptokurtic population.

Table 1: Grain size distribution and quantitative parameters of Idah sandstone samples of Ajali Formation

Sample	Mean (mm)	Sorting (ϕ)	Skewness (ϕ)	Kurtosis
OR1	0.66 Coarse-grained sand	1.2 Poorly sorted	-1.00 Strongly coarse skewed	0.64 Very Platykurtic
OR2	0.62 Coarse-grained sand	1.46 Poorly sorted	-0.76 Strongly coarse skewed	0.82 Platykurtic
OR3	1.00 Medium-grained sand	1.12 Poorly sorted	-0.94 Strongly coarse skewed	1.81 Very Leptokurtic
0R4	0.99 Coarse-grained	0.95 Moderately	-0.116 Coarse	0.71 Platykurtic

	sand	sorted	skewed	
OR5	1.13 Medium-grained sand	0.94 Moderately sorted	-0.153 Coarse skewed	0.83 Platykurtic
OR6	1.12 Medium-grained sand	0.88 Moderately sorted	-0.151 Coarse skewed	1.14 Leptokurtic
OR7	1.54 Medium-grained sand	1.17 Moderately sorted	-0.94 Strongly coarse skewed	1.30 Leptokurtic

4.4.1. Linear Discriminant Function Analysis

The Y1 equation of Sahu (1964) was used in the discrimination between aeolian and littoral (intertidal zone) environments. The equation suggests an aeolian environment for values of Y1 less than – 2.7411 and a beach environment for values of Y1 greater than – 2.7411. The result (Table 2) suggests a 100% beach environment for Y1. The Y2 equation discriminated between the Beach (backshore/foreshore) and shallow agitated marine environments. A less than 63.3650 value of Y2 suggests a beach deposition, whereas if it is greater than 63.3650, a shallow agitated marine environment is inferred. A shallow agitated marine (subtidal) environment is suggested since 85.71% of the values of Y2 calculated are greater than 63.3650.

The Y3 equation discriminates between shallow marine (subtidal) and fluvial, deltaic environments. If Y3 is less than -7.419, a fluvial-deltaic environment is inferred. However, if Y3 exceeds -7.419, it is identified as a shallow marine (subtidal) deposit. The analysis revealed that 71.42% of the plotted Y3 values suggested a shallow marine environment. In comparison, 28.57% revealed Y3 values less than -7.419, indicating a fluvial-deltaic setting (Fig. 4 and Fig. 5). Overall, a shallow marine environment with minimal fluvial influence is suggested.

Table 2: Linear Discriminant Function of OR- Idah Sandstone Facies of Ajali Formation

Sample ID	Y1	Remark	Y2	Remark	Y3	Remark
OR1	7.0441	Beach	98.6880	Shallow Agitated Marine (subtidal)	-7.5028	Fluvial deltaic
OR2	9.8090	Beach	151.1827	Shallow Agitated Marine (subtidal)	-14.7386	Fluvial deltaic

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OR3	6.7003	Beach	114.551	Shallow Agitated Marine (subtidal)	-6.017	Shallow Marine
OR4	4.4267	Beach	66.9333	Shallow Agitated Marine (subtidal)	-1.9137	Shallow Marine
OR5	4.9981	Beach	63.407	Shallow Agitated Marine (subtidal)	0.1082	Shallow Marine
OR6	5.5486	Beach	62.1701	Beach (backshore)	0.9785	Shallow Marine
OR7	5.5708	Beach	121.0903	Shallow Agitated Marine (subtidal)	-6.8906	Shallow Marine
Sample ID	Y1	Remark	Y2	Remark	Y3	Remark
OR1	7.0441	Beach	98.6880	Shallow Agitated Marine (subtidal)	-7.5028	Fluvial deltaic
OR2	9.8090	Beach	151.1827	Shallow Agitated Marine (subtidal)	-14.7386	Fluvial deltaic
OR3	6.7003	Beach	114.551	Shallow Agitated Marine (subtidal)	-6.017	Shallow Marine
OR4	4.4267	Beach	66.9333	Shallow Agitated Marine (subtidal)	-1.9137	Shallow Marine
OR5	4.9981	Beach	63.407	Shallow Agitated Marine (subtidal)	0.1082	Shallow Marine
OR6	5.5486	Beach	62.1701	Beach (backshore)	0.9785	Shallow Marine
OR7	5.5708	Beach	121.0903	Shallow Agitated Marine (subtidal)	-6.8906	Shallow Marine

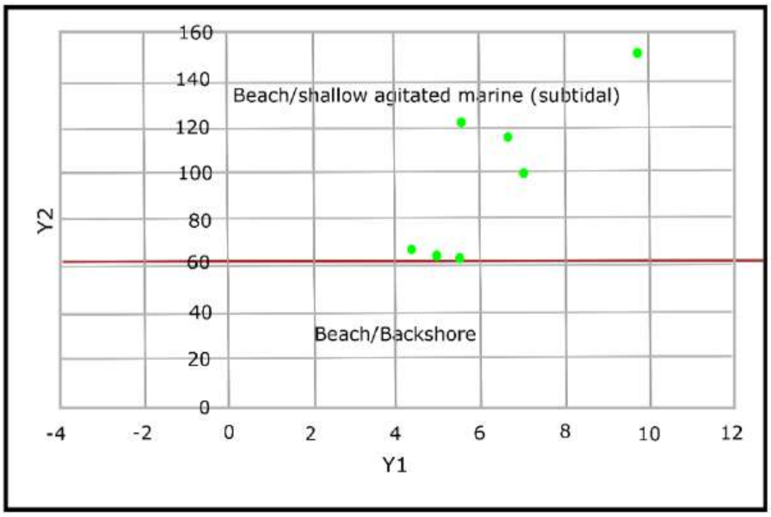

Figure 4: Linear Discriminate Function Y1/ Y2 scatter plot for the sandstone facies in the study area

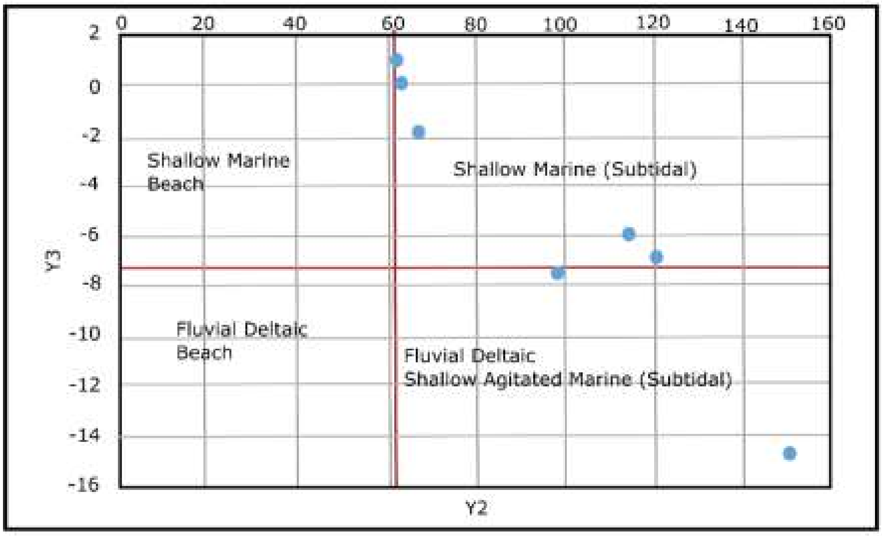

Figure 5: Linear Discriminate Function Y2/ Y3 scatter plot for the sandstone facies in the study area

4.5. Petrography

The petrographic examination of the clastic grains from the study area revealed the dominance of sub-rounded to rounded grains of quartz associated with biotite, opaque minerals, and rock fragments (PLATE 2). From the result in TABLE 3, quartz makes up the dominant framework mineral, with an average of 73% of the mineral constituents showing undulose extinction and visible poor cleavage in both plane and cross-polarised light.

Also, biotite mineral constitutes an average of 6.6% exhibiting numerous dark brown to black pleochroic haloes under plane-polarised light and a mottled appearance characteristic of micaceous minerals near extinction under cross-polarised light. The result further reveals the presence of rock fragments and opaque minerals, making up 8.5% and 11.84% of the minerals, respectively.

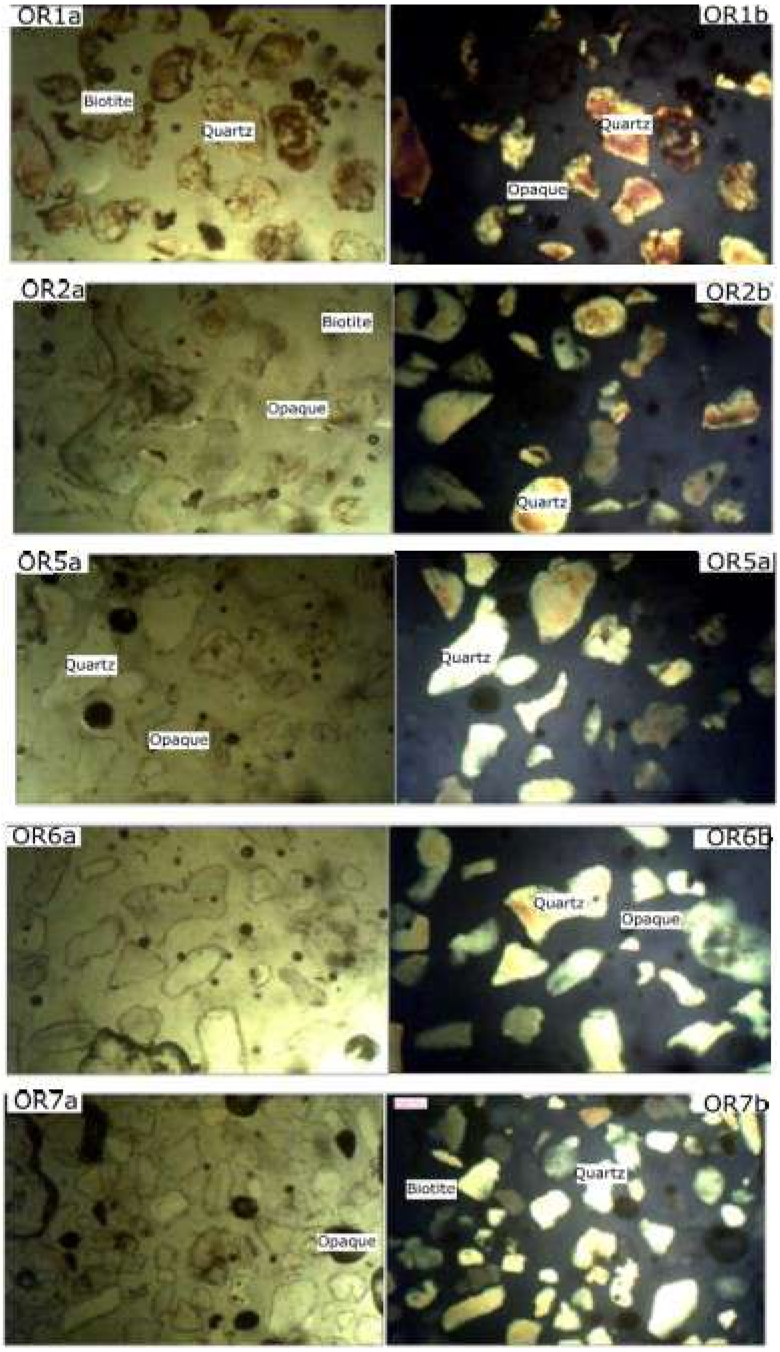

Plate 2. Photomicrograph showing OR1, OR2, OR3, OR4, OR5, OR6 and OR7 in a plane and cross-polarised light (×20) showing sub-round grains dominated by quartz minerals

Table 3: Average modal composition of OR samples

Minerals present	OR1	OR2	OR5	OR6	OR7	Average Percentage Composition
Quartz	60.64	66.04	76.36	78.29	83.97	76.06
Biotite	5.32	4.72	8.18	8.53	6.11	6.6
Opaque	22.34	16.98	9.09	6.98	3.82	11.84
Fragments	11.70	12.26	6.36	6.20	6.11	8.5
Total	100.00	100.00	100.00	100.00	100.00	100.00

5. DISCUSSION

5.1 Environment of Deposition

The results (Table 1) of the mean size of the sediments exhibit a medium (59.14 %) to coarse (42.86%) grained texture ranging in value from 0.62φ to 1.54φ. The graphical standard deviation shows that the measure of sorting of the sediments varies from moderately well sorted to poorly sorted, with an average value of 1.10φ indicative of poorly sorted sediment. The average degree of asymmetry of the grain size distribution is strongly coarse skewed, and the kurtosis value suggests platykurtic to leptokurtic, with most of the samples having a leptokurtic population (Folk & Ward, 1957; Ilevbare & Omodolor, 2020; Okoro et al., 2020; and Alege et al., 2022). The platykurtic to leptokurtic attributes of the sediments with a prevalence of the leptokurtic population reflect the variation in the current velocities of the depositing medium (Allen, 1980; and Baruah et al., 1997).

The moderately to poorly sorted, coarse to medium-grained sandstone of the Ajali Sandstone outcropping in Idah indicates fluctuations in depositional energy, suggesting tidal influence interaction in the shallow marine settings. The sandstone's moderately to poor sorting characteristics reflect less reworking during sediment transport, indicating rapid fluvial depositional process (Friedman, 1967; Adamu et al., 2018; and Okoro et al., 2020). The skewness reveals the dominance of strongly coarse skewed, also interpreted as the attribute of deposition in a moderate to high-energy environment due to tidal influence (Ayodele & Madukwe, 2019; Kroonenberg, 1992; and Ocheli et al., 2018).

The linear discriminant function plot of Sahu (1964), as presented in Table 2 and Figs. 4- 5, delineated three primary environments as YI= beach environment (100%); Y2 = shallow agitated marine (subtidal) environment; and Y3 = shallow marine environment (71.42%). Overall, a beach environment with tidal influence is suggested for the sediments of the Ajali Sandstone outcropping in Idah. This environment corresponds with the same environment suggested by (Amaral & Pryor, 1977) and Kar et al. (2020) using textural characteristics for St Peter Sandstone of Wisconsin and Kalijhora Gondwana Basin in Darjeeling District, India, respectively.

5.2. Provenance

Petrographic examination of the samples reveals the presence of the following mineral constituents in the study area: quartz (76.06%), biotite (6.6%), opaque (11.84%) and lithic fragments (8.5%) (Plate 2; Table 3). The dominance of sub-rounded grains of quartz associated with biotite, opaque minerals and rock fragments indicate textural maturity as a result of abrasion due to transport in a high to moderate-energy environment that tends to separate grains into different sizes (Folk, 1974). The lack of feldspar in the mineralogical association also supports this. Furthermore, the mineralogical maturity of the quartz-rich sandstones (quartz-arenites) and the absence of feldspar minerals in the mineralogical composition of sandstones suggest a high degree of sediment reworking in a highly humid climate that promotes rapid chemical weathering aiding the destruction of feldspathic fragments in the source area (Edegbai et al., 2019; Enyioko et al., 2022; Nichols, 2009; Okoro & Igwe, 2014; Onyekuru, 2009).

The percentage of quartz minerals present in samples OR1, OR2, OR5, OR6 and OR7 are 60.64%, 66.04%, 76.36%, 78.28% and 83.97% (Table 3), respectively. The increasing percentage of quartz from OR1 to OR7 suggests sandstones derived from topographic highs distantly from the depositional area. Also, the high dominance of quartz minerals (73%) and an absence of feldspar indicate granitic rock derivatives and a long transportation history from a distant provenance. These suggest contributions from the Santonian Okigwe-Abakaliki anticlinorium and Precambrian Basement Complex rocks of Cameroun, in southeast Nigeria. This age corroborates the findings of Hoque (1976), Whiteman (1982), Amajor (1987),Agumanu (1993) and Tijani et al. (2010) on the multiple probable provenances of Ajali Sandstone.

The presence of biotite mineral and the absence of muscovite suggests the parent deposit is that of volcanic sources, as muscovite usually indicates metamorphic rocks, and when present in igneous rocks, they are typically restricted to the felsic varieties (Blatt, 1980; Tucker, 2001; Nichols, 2009) which is absent in the study area. Likewise, lithic fragments in minute proportion (Table 3) indicates long transport from the parent rock since the fragments resist abrasion. Also, the lithic fragments suggest sediments derived from a high-relief environment (Nichols, 2009).

Therefore, the integrated analysis presented here suggests that the Ajali Sandstone in the study area is likely sourced from the nearby northeast-trending anticlinorium of Santonian Okigwe-Abakaliki or sediment input from both sources. This further affirms the post-Santonian age of the Ajali Sandstones in a continental shelf environment as proposed by previous investigations at different localities (Adamu et al., 2018; Tijani et al., 2010; Adamu et al., 2018; Nwajide, 2022).

6. Conclusion

The environment of deposition and provenance investigations of the Ajali Sandstone Formation outcropping in Idah of the Northern Anambra Basin, Nigeria, were carried out using textural characteristics and petrographic analyses. Granulometric analysis reveals that grain sizes range from medium to coarse, with grain sorting ranging from moderately to poorly sorted. Kurtosis result shows the sandstones are platykurtic to leptokurtic, with most of the samples having a leptokurtic population. Skewness values with a dominance of strongly coarse skewed, suggest deposition in a high energy environment due to tidal influence. The linear discriminant plot results suggest a shallow marine environment with minimal fluvial impact.

Results from the thin section analysis reveal a high dominance of quartz minerals and a conspicuous absence of feldspar indicative of high maturity and a granitic rock derivative. Also a long transportation history is indicated from the adjacent northeast-trending Okigwe-Abakaliki anticlinorium of Santonian age that further supports the post-Santonian age of the Ajali Sandstones in a continental shelf environment.

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