Adamu, L. M.

Recognizing the of key petroleum system elements from outcrops of the Northern Anambra Basin, Central Nigeria.

Department of Earth Sciences,
Kogi State University,
Anyigba, Nigeria.
Email: adamulm@ksu.edu.ng

RECOGNIZING THE OF KEY PETROLEUM SYSTEM ELEMENTS FROM OUTCROPS OF THE NORTHERN ANAMBRA BASIN, CENTRAL NIGERIA.

Adamu L. M. [1]; Obaje, N. G.[2]; Alege, T. S.[3]; Odoma, A. N.[3]; Ebeh A.[1]; Ohiemi A.F.[4]; Ochu, G.D.[1]; Umar, M.U.[2]; Etukudo, N.J.[5]; Adesina, D. A.[1]; Isaac, O. B.[4].

[1]Department of Earth Sciences, Kogi State University, Anyigba, Nigeria.
[2]Department of Geology, Ibrahim BadamasiBabangida University, Lapai, Niger State, Nigeria.
[3]Department of Geology, Federal University Lokoja, Kogi State, Nigeria.
[4]Department of Geosciences, Confluence University of Science and Technology Osara, Kogi State, Nigeria.
[5]Department of Geology, AkwaIbom State University, MkpatEnin, AKS, Nigeria.
Email: lukman10musa@yahoo.com, adamulm@ksu.edu.ng

ABSTRACT

Compared to its southern counterpart, the northern Anambra Basin in central Nigeria is still relatively unexplored despite having significant potential for oil development. Across important lithostratigraphic units, including the Mamu, Ajali, Nsukka, and Nkporo formations, this study provides outcrop-based evidence of the essential components of the petroleum system: source, reservoir, seal rocks, and entrapment characteristics. Through detailed geological field mapping and comparative facies analysis, the work highlights organic-rich shales and coals within the Mamu and Nsukka formations as potential source rocks, supported by geochemical proxies such as TOC values, HI indices, vitrinite reflectance, and biomarker data. The Ajali Formation, composed of well-sorted, cross-bedded quartz arenites, displays favourable reservoir properties, including high porosity, permeability, and bioturbation features. Intraformational and regional seals are identified in the Mamu and Nsukka shales, respectively, based on geotechnical indices and deformation characteristics. Effective hydrocarbon trapping mechanisms are provided by structural and stratigraphic traps, such as clay-smearing along fracture zones and syn-sedimentary growth faults. The continuity of the facies suggests a potential lateral connection between reservoirs, and the outcrop exposures reveal further sedimentary successions indicative of paralic, tidal, and shallow marine depositional environments. The comparison of the northern and southeastern regions highlights heterogeneities in facies architecture, maturity, and structural complexity. Comparing the northern and southeast parts highlights the differences in facies architecture, maturity, and structural complexity. The northern Anambra Basin possesses all the elements necessary for a functioning petroleum system, according to current subsurface correlations and outcrop analogues. This work contributes to the understanding of Nigeria's interior basins and supports future hydrocarbon production projects by providing a surface-based evaluation of petroleum system dynamics.

Keywords: Nigeria, Northern Anambra Basin, Outcrops, Petroleum system elements.

1.0 INTRODUCTION

While many studies have been conducted in the Anambra Basin, most have focused on aspects like the size of the basin, its geological development, the types of sediments, and the age and characteristics of the rocks, as well as the environments where these sediments were deposited. Only a few of these studies have specifically looked at the potential for finding hydrocarbons. Only a handful of these studies have explicitly aimed at hydrocarbon prospectivity (Obaje et al. 1999, 2004; 2013; Anyiam et al. 2015; Dim et al. 2018; Obaje et al. 2020; Adamu et al. 2022b; Yusuf et al. 2023). In order to fully understand the Anambra Basin's hydrocarbon potential, more research is necessary. The absence of subsurface data in Nigeria's inland basins, particularly in the northern Anambra Basin, makes the upper Cretaceous layers of north-central Nigeria challenging to interpret stratigraphically and structurally and to produce petroleum. The petroleum system's fundamental elements such as source, reservoir, and seal (or cap) rocks are better understood in this research thanks to surface data collected from numerous outcrop locations as part of a continuous evaluation of the region's petroleum prospectivity. Using surface data to verify these fundamental components is the first step in examining the potential for oil and gas in sedimentary basins worldwide. Processes such as trap formation and the production, movement, and accumulation of hydrocarbons are also part of the process of creating an active petroleum system (Magoon and Dow 1994). This study focuses on the northern portion of the Anambra Basin, examining the Campanian to Maastrichtian rock outcrops (Fig. 1). Idah-Ocheche Cliff, Ajaka-Ogbogba Hills, Idah-Aya-Ojuwocha, Ajegu-Ojodu, Ochadamu-Anyigba, Ugwolawo-Anyigba, Iyale-Omala, Egume, Ankpa-Okaba-Okobo-Awo-Odu, and the Edumogo River areas of north-central Nigeria are among the locations covered in the study (see Fig. 2).

2.0 STRATIGRAPHY OF ANAMBRA BASIN

The pre-Santonian layers experienced elevation and folding as a result of worldwide tectonic shifts during the mid-Santonian epoch (Guiraud and Bosworth, 1997). Intense folding into the Abakaliki anticlinorium and some small volcanic activity occurred in the Abakaliki region. The smaller Afikpo syncline to the southeast and the larger Anambra Basin to the northwest are the depressions that resulted from this folding on each side of the anticlinorium. The mid-Santonian folding caused an initial transgression and a subsequent regressional phase in the Southern Benue Trough, establishing the Anambra Basin as the new depocenter where fluvio-deltaic sandstones of the Ajali Formation, Campanian-Maastrichtianshales of the Enugu and Nkporo Formations, and coal deposits of the Mamu Formation accumulated. The Upper Cretaceous proto-Niger Delta no longer advanced in the Southern Benue Trough after a major transgression in the Palaeocene

(Zaborski, 2000). The Imo Shale and the Ameki Formation were deposited in the Anambra Basin, which is where sedimentary processes were restricted.The four main litho-stratigraphic units that make up the research region are Cretaceous and newer sediments (Fig. 1), and they are part of the northern Anambra Basin (Fig. 2) (Odumoso et al., 2013). Together with the Enugu and Owelli Shales, which are its lateral counterparts, the Nkporo Shale forms the base of this lithostratigraphic succession. The Campanian epoch is when these units were produced, and they are linked to short marine transgressions that were followed by regressions. From a lithological perspective, they consist of sandstone components with deltaic origins and carbonaceous shales (Nwajide & Reijers, 1996). These units have bedding planes that contain early diagenetic minerals such siderite and pyrite, however they seem to be poorly defined (Odumoso et al., 2013). The Maastrichtian period saw the deposition of the Mamu Formation's floodplain sediments and deltaic forest due to the wide sea's shallow depth. In terms of lithology, this formation shows a pattern of cyclic deposition of shales and sandy shales, with coal occasionally found on top of the carbonaceous shale and sandy shale (Whiteman, 1982). According to Fatoye and Yomi (2013), the Ajali Sandstone and Nsukka Formation, which are situated on top of the Mamu Formation, contain coarse and gravely sandstones in their upper levels and change to medium- to fine-grained sandstones at deeper depths. Layers of clay and coal near the borehole's bottom most likely represent the areas where the Ajali Sandstone and the coal-bearing Mamu Formation meet (Nwankwor et al., 1988). The Danian-era Nsukka Formation caps the succession in the Anambra Basin (Nwajide, 2013). According to Reyment (1965), the Nsukka Formation is made up of thin coal layers, plant-rich beds, sandstones, and gray sandy shales that alternate in layers. This formation, according to sedimentological study, is the result of fluvial-deltaic sedimentation that began close to the end of the Maastrichtian and lasted into the Paleocene (Agagu et al., 1985).

African Journal of Engineering and Environment Research Vol.8(1) 2025 pp 1- 31
©2025 CEFPACS Consulting Limited. www.cefpacsconsultingltd.org.ng
P-ISSN: 2992-2828; E-ISSN: 2714-2264

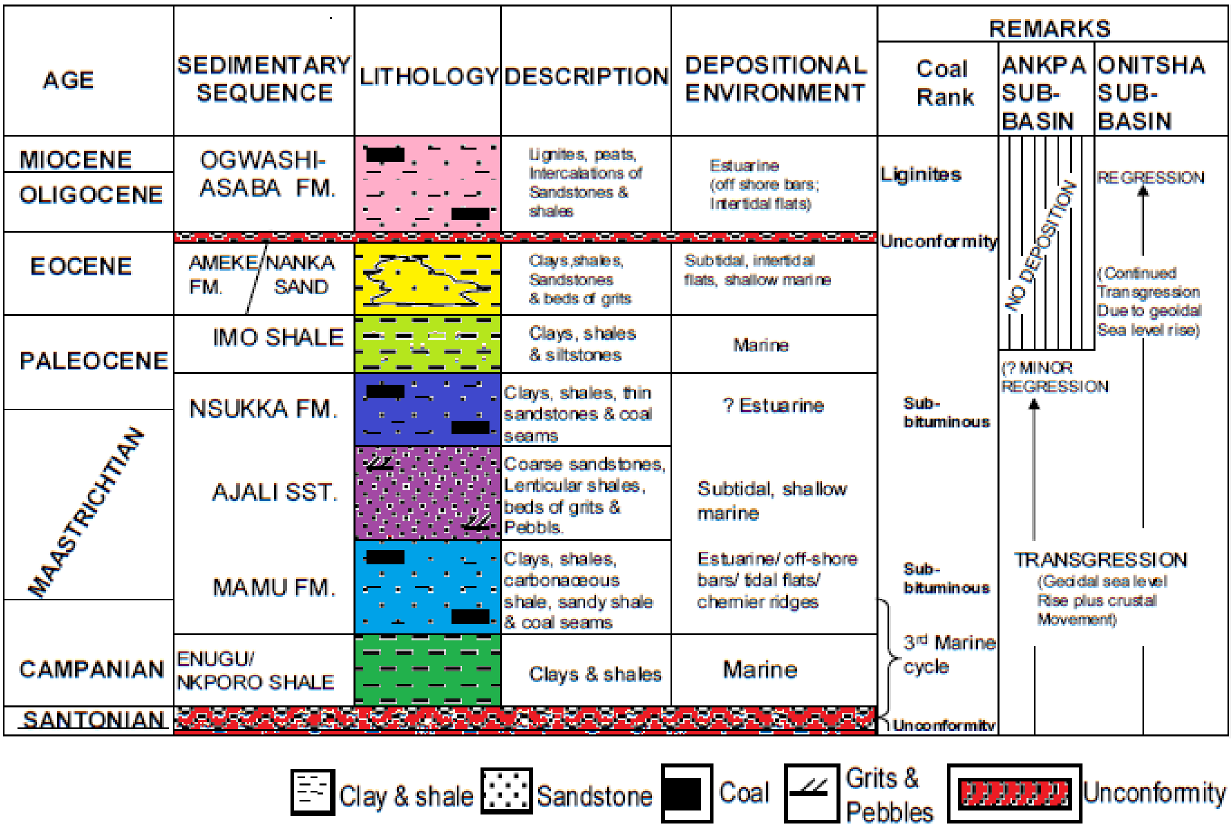

Fig. 1: Regional Stratigraphic succession of the intra-continental rifted Anambra Basin.

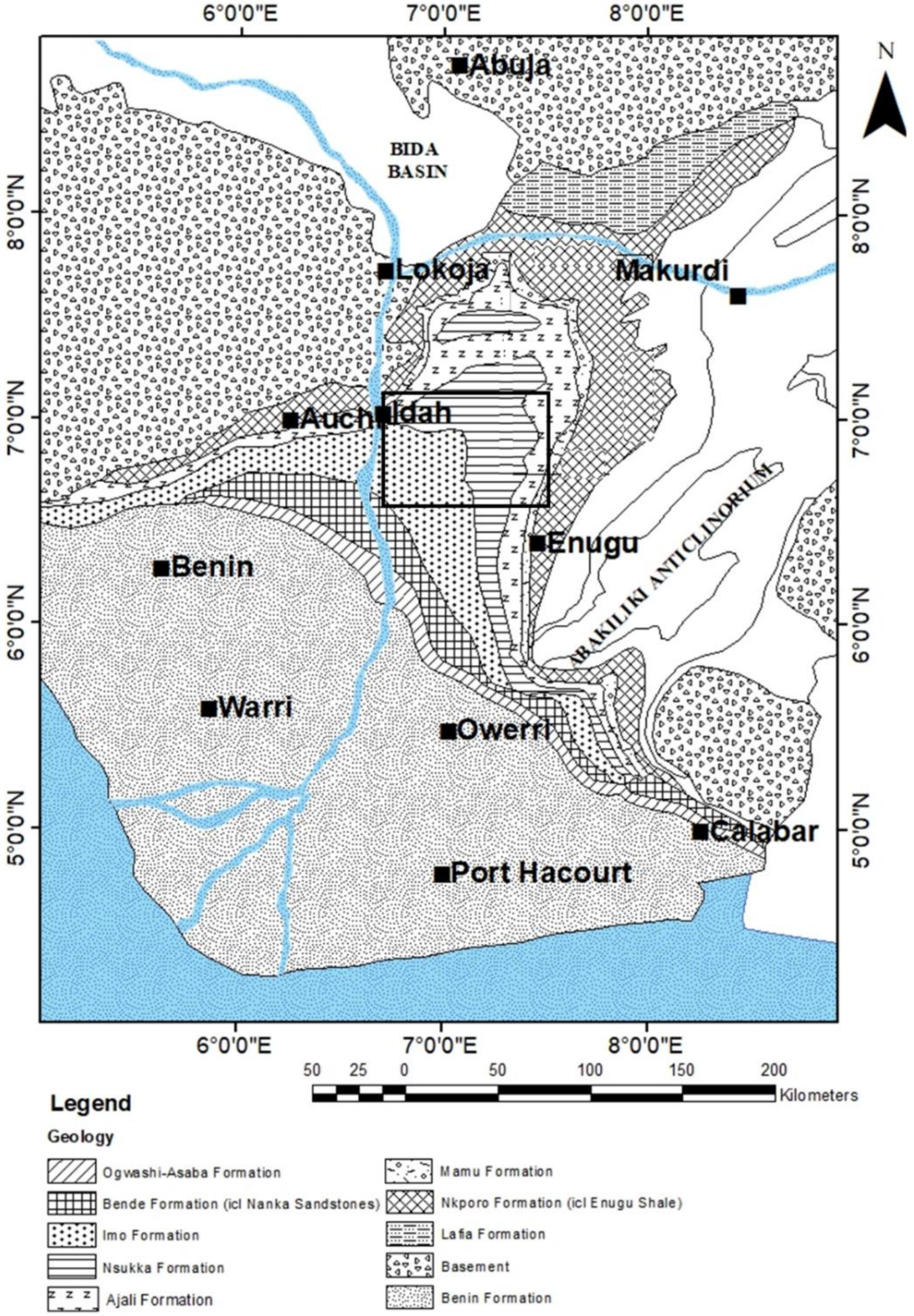

Fig. 2: Regional Geology and stratigraphy of the southern Nigeria showing location of study site (modified from Obaje, 2009).

3.0 METHODOLOGY

In the northern Anambra Basin, outcrops that are indicative of the lithostratigraphic units were visited and examined. The methods described in Adamu and Ayuba (2019) were followed in order to perform detailed inspections of the outcrops, geological formation research, sedimentological logging, and recording of specific outcrop sections. Various lithologies were identified and described by the type, color, grain size, and textural characteristics of the rock as well as the related depositional, biogenic, and syn-sedimentary structures (Figs. 3–16). We identify and analyze potentially important elements of the petroleum system(s) using the detected facies.

4.0 RESULTS AND DISCUSSION

4.1 Field Relationship of exposed lithostratigraphic units

The Northern Anambra Basin exposures comprises of the Mamu, Ajali, and Nsukka Formations. The lithofacies ranges from shale, sandstone, clay, siltstone, and coal (Figs. 3 – 16).

4.1.1 Mamu Formation

On a small ridge that trends NE-SW, the representative outcrops of this Mamu lithostratigraphic unit can be seen along road-cut exposures along the Itobe–Anyigba express road, the OjuwoOcha, Ajegu, and Idah by-pass roads (Figs. 3–7). Nearly horizontal sedimentary units, with maximum dips of 5° to 7° to the southwest, show that significant tectonic deformation did not significantly impact the region. Beds vary in thickness from 0.25 to 3.2 meters. Shale, silty-shale, claystone, siltstone, extremely fine and fine-to-medium-grained sandstone, and heteroliths are examples of lithologies (Fig. 6a).The logged sections exhibit recurring cycles of clay units, carbonaceous shale, heterolith, and sandstone. Shale, silty-shale, black carbonaceous/coaly shale, coal, heteroliths, and very fine and fine-to-medium-grained sandstone, siltstone, claystone, and river channels in the Olamaboro, Omala, and Ankpa (okaba, Okobo, Awo, etc.) areas are representative outcrops of this Mamu lithostratigraphic unit. Carbonaceous shale, coal deposits, siltstone, and heterolithic strata are recurrent sequences that characterize the logged sections. The coal seams are dull to dazzling in luster and exhibit columnar joint structures. Around these deposits are intervals of shale and carbonaceous and heterolithic sand. Additionally, somewhat altered fundamental sedimentary features including hummocky and swaley cross-stratification are visible, in addition to fractures seen in the fine-grained sandstone layers at the upper portions of the Mamu Formation. Additional significant sedimentary features include parallel and wave-ripple laminations, tabular and trough cross-beds, and horizontal and vertical burrows with varied levels of bioturbation. These sedimentary deposits, which include coal, carbonaceous shale, sandstone, siltstone, and heterolithic facies, are found in lagoons, swamps, barrier islands, shoreface, offshore-transition zones, and offshore habitats (Adedosu et al. 2014; Odumodu 2014; Adamu et al. 2018c).

Fig. 3: Outcrops of Mamu Formation in Ojodu, along Lokoja-Anyigba Expressway, central Nigeria. (a,b**)** Road-cut section showing well bedded, fissile grey shale interbed with siltstone and clays

Fig. 4: Outcrops of Mamu Formation. (a,b) Milky white to light grey clayey siltsone, and white, well bedded claystone facies exposed in area around Aloji village, along Itobe-Anyigba Expressway, central Nigeria

African Journal of Engineering and Environment Research Vol.8(1) 2025 pp 1- 31
©2025 CEFPACS Consulting Limited. www.cefpacsconsultingltd.org.ng
P-ISSN: 2992-2828; E-ISSN: 2714-2264

Fig. 5: Mamu Formation exposed (a) in the vicinity of Achago village, Central Nigeria. A photo of a laminated bioturbated (the arrow) siltstone bed that is white to dark orange is accompanied by milky white to reddish silty clay that leads upward into a bed of ferruginized amber to dark grey, weakly stratified siltstone with an erosional base beneath a bed of reddish siltstone that is covered by lateratized siltstone (07^{o} 19' 48.1''N, 06^{o} 47' 02.8''E), (b) North of Ukunube town. Photograph showing fine-grained sandstone overlain by intercalation of grey to bluesh mud, and siltstone (07^{o} 21' 15.1''N, 06^{o} 47' 06.2''E), (c) Along Ocheche River near Idah. Photograph showing the medium to coarse-grained tabular cross bedded sandstone. Blue arrows pointing at reactivation surfaces, (d) along Ocheche River near Idah. Photograph showing vertical section of intercalation of white and grey, medium to coarse-grained, highly bioturbated, tabular cross-bedded sandstone with erosional surfaces (07^{o} 07' 27''N, 06^{o} 44' 20.6''E)

African Journal of Engineering and Environment Research Vol.8(1) 2025 pp 1- 31
 www.cefpacsconsultingltd.org.ng
P-ISSN: 2992-2828; E-ISSN: 2714-2264

Fig. 6: Road cuts of Mamu Formation exposed in (a,b) Agbenema-Efe showing beds of very fine-grained sandstone, well bedded claystone, interbeds of clayey siltstone and fissile shale and ferruginised siltstone-claystone

Fig. 7: (a) Road cuts of Mamu Formation exposed in Agbenema-Efe showing beds of very fine-grained sandstone, well bedded claystone, interbeds of clayey siltstone and fissile shale and ferruginised siltstone-claystone, (b) Coal facies, carbonaceous shale, and clay facies of Mamu Formation exposed at Awo-Akpali mining site, Ankpa

4.1.2 Ajali Formation

Quarry sections in Ogbogba, Iyale, Ochadamu, Hills, GRA Idah, Ocheche Cliff, Anyigba, Adumu-Ochadamu–Anyigba Road, and Iyale area, all in Kogi State, northcentral Nigeria, reveal outcrops of the Ajali lithostratigraphic unit (Figs. 8–11). Very thick, friable to reasonably cemented sandstone units with interstratified thin clay bands make up exposed parts. The fine, medium, coarse, and partially pebbly grain sizes of sandstone are distinguished by extensive planar and herringbone cross-bedding with reactivation surfaces. Cross-bed laminae foresets are distinguished by mud drapes and show typical grading. The main sedimentary formations are distorted by bioturbation, which is evident in sandstones. There are fossilized and deeply buried clay band intervals, particularly in the Ocheche cliff area. Wave-rippled surfaces that have been preserved at the Ocheche cliff section and sporadic joints among consolidation sandstones are examples of other sedimentary features. The Ajali Formation's sandstone and layered claystone features show sedimentary layers that were deposited in tidal shelf and fluvio-tidal channel environments (Ladipo 1988; Adamu et al. 2018a; Adamu et al. 2018b; Adamu et al. 2017).

Fig. 8: Outcrops of Ajali Formationvery thick sandstone characterized by interstratified thin clay bands exposed at a quarry section in Iyale Hills, Ochadamu-Anyiba road, NC Nigeria

African Journal of Engineering and Environment Research Vol.8(1) 2025 pp 1- 31
©2025 CEFPACS Consulting Limited. www.cefpacsconsultingltd.org.ng
P-ISSN: 2992-2828; E-ISSN: 2714-2264

Fig. 9: (a) Shows a thick sandstone unit with ripple mark structures revealed at the GRA Idah part of the Ajali Formation, and (b) shows a thick sandstone unit with interlaminated clay bands with reactivation surfaces exposed at the Ocheche section of Idah, NC, Nigeria. Ocheche cliff section displaying the Ajali Formation's thick sandstone package with (c,d) large-scale planar, trough, and herringbone cross-bedding, reactivation surfaces, and visible clay draping. (e) At Ocheche, pebbly sandstone units of the Ajali Formation are seen. (f) Thick sandstone unit with basal section showing sandstone interstratification, bioturbation, tabular cross-bedding, and

reactivation structures exposed at Ocheche River cliff section, Idah, NC Nigeria

Fig. 10: Outcrops of Ajali Formation**.** (a,b,c,d)Thick sandstone unit with basal section showing sandstone interstratification, bioturbation, tabular cross-bedding, and reactivation structures exposed at Ocheche River cliff section, Idah, NC Nigeria

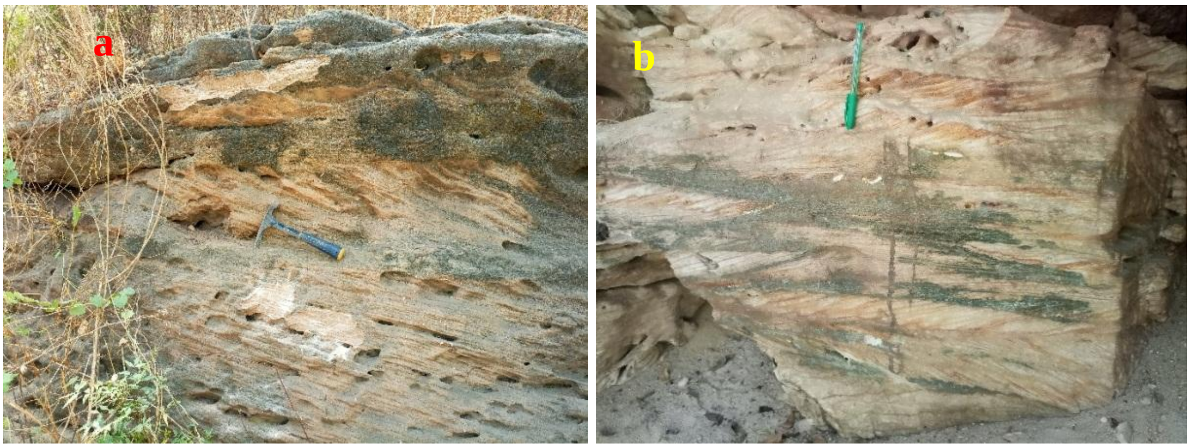

Fig. 11: (a,b) Photograph of Ocheche cliff sections of Ajali Formation. The exposures are characterized by thick sandstone package with large-scale planar, trough, and herringbone cross-bedding, reactivation surfaces, and visible clay draping

African Journal of Engineering and Environment Research Vol.8(1) 2025 pp 1- 31

P-ISSN: 2992-2828; E-ISSN: 2714-2264

4.1.3 Nsukka Formation

In the Ayingba-Iyale road-cut and quarry section, as well as in some locations like Egume, Ogbogba, Iyale, and Omala, outcrops of the Nsukka lithostratigraphic unit are visible as patches on the Ajali Formation Hills except in Edumogo where they were exposed along river channels (Figs. 12a – f). Lateralized shale, clay, and siltstone are lithologies, as are thick siltstone, claystone, fine- to medium-grained sandstone that forms a sharp contact with dark to yellow thick shale layers. Primary sedimentary features seen in the Idah section include heavily bioturbated and burrowed sandstone strata, as well as current-rippled surfaces. Interbeds of sandstone, shale, coal, and heterolith are sporadic. Seldom found coal, sandstone, shale, and heterolith in the Nsukka Formation indicate sediment packages that were deposited in shoreface, offshore, and lagoon/bay environments (Umeji and Nwajide 2007; Adamu et al. 2018a; Adamu et al. 2018b).

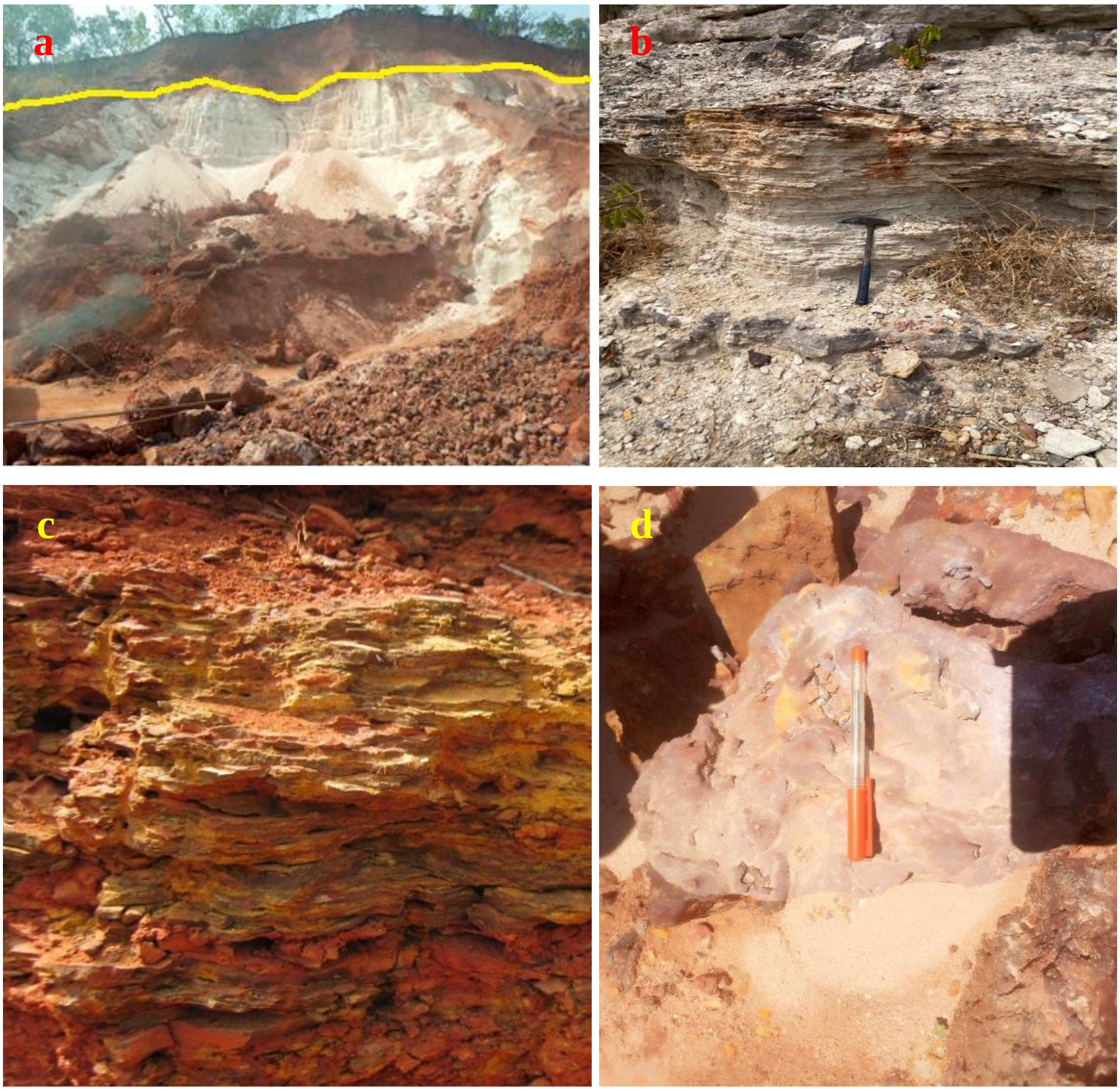

Fig. 12: Outcrops of Nsukka Formation. (**a)** as patches on Iyale Hills showing lateratized shales and claystone (indicated by yellow line), (**b) t**hick shale overlain by sandstone in Nsukka Formation, outcropping at a road-cut section, km 15 on both side of Iyale–Omala road. (**c,d)** shale facies of the Nsukka Formation exposed at the top of Ogbogba and Iyale Hills. (**e,f)** Nsukka Formation exposed at Edumogo showing shale, coal, and claystone facies.

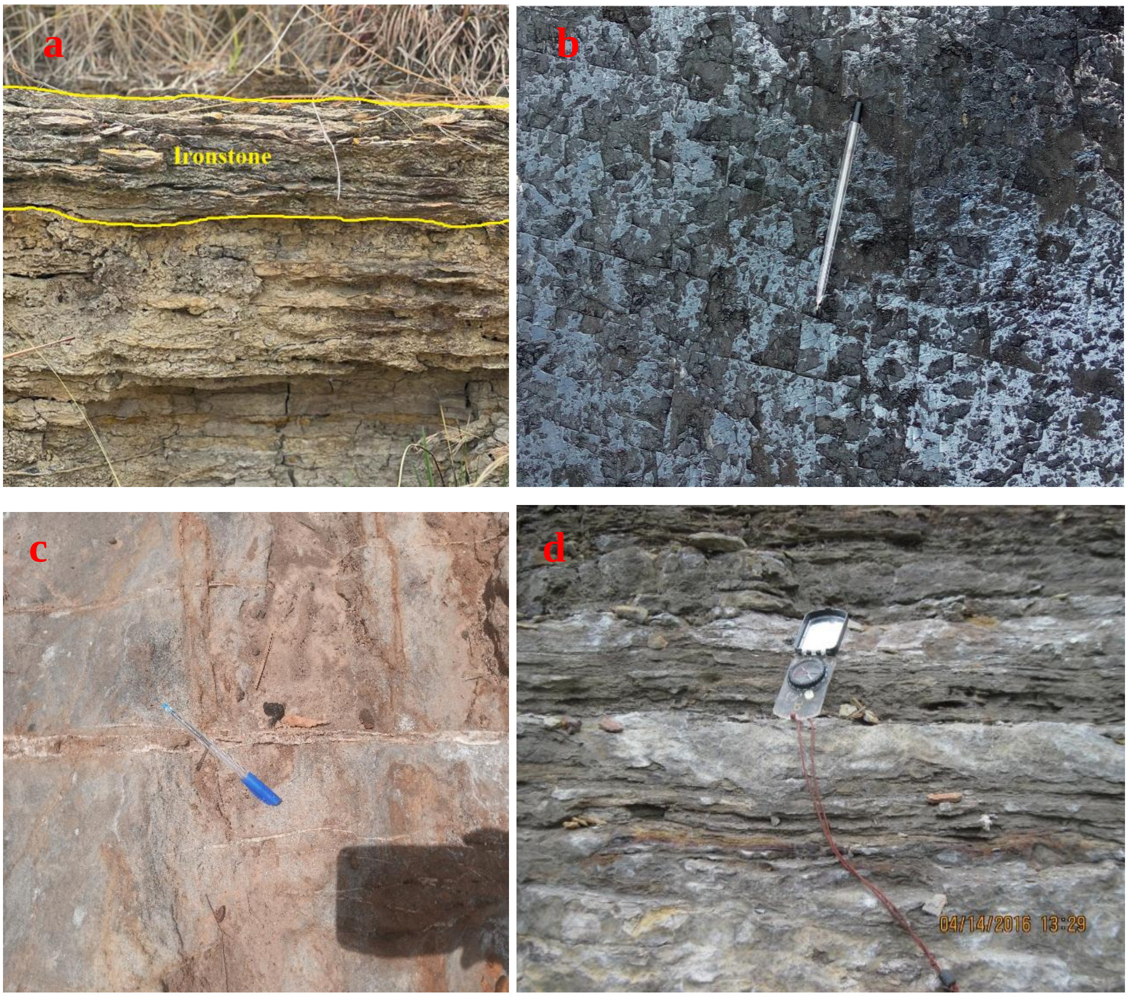

Fig. 13: Possible source and seal rock outcrops in the Northern Anambra Basin. (**a)** Bands of ironstone and siltstone are visible in the Mamu Formation's basal shale layers in a portion of the river channel in Omala, off the Omala-Anyigba road in Central Nigeria. (**b)** At the Awo Akpali quarry section in Ankpa, Central Nigeria, the Mamu Formation's coal bed is exposed. (**c)** Close-up of an anastomosing joint that may act as a conduit for fluid movement in the basal shale unit. (**d)** At the base of the Ojodu road cut, along the Lokoja-Anyigba expressway in Central Nigeria, dark-gray shale from the Mamu Formation is visible. (**e)** Dark-gray plastic shale of Nsukka Formation exposed at basal section of Edumogo village, Igalamela, Central Nigeria. (**f)** Coal bed of Nsukka Formation exposed at the base of thick carbonaceous shale in river channel at Edumogo village, Igalamela, Central Nigeria.

African Journal of Engineering and Environment Research Vol.8(1) 2025 pp 1- 31

P-ISSN: 2992-2828; E-ISSN: 2714-2264

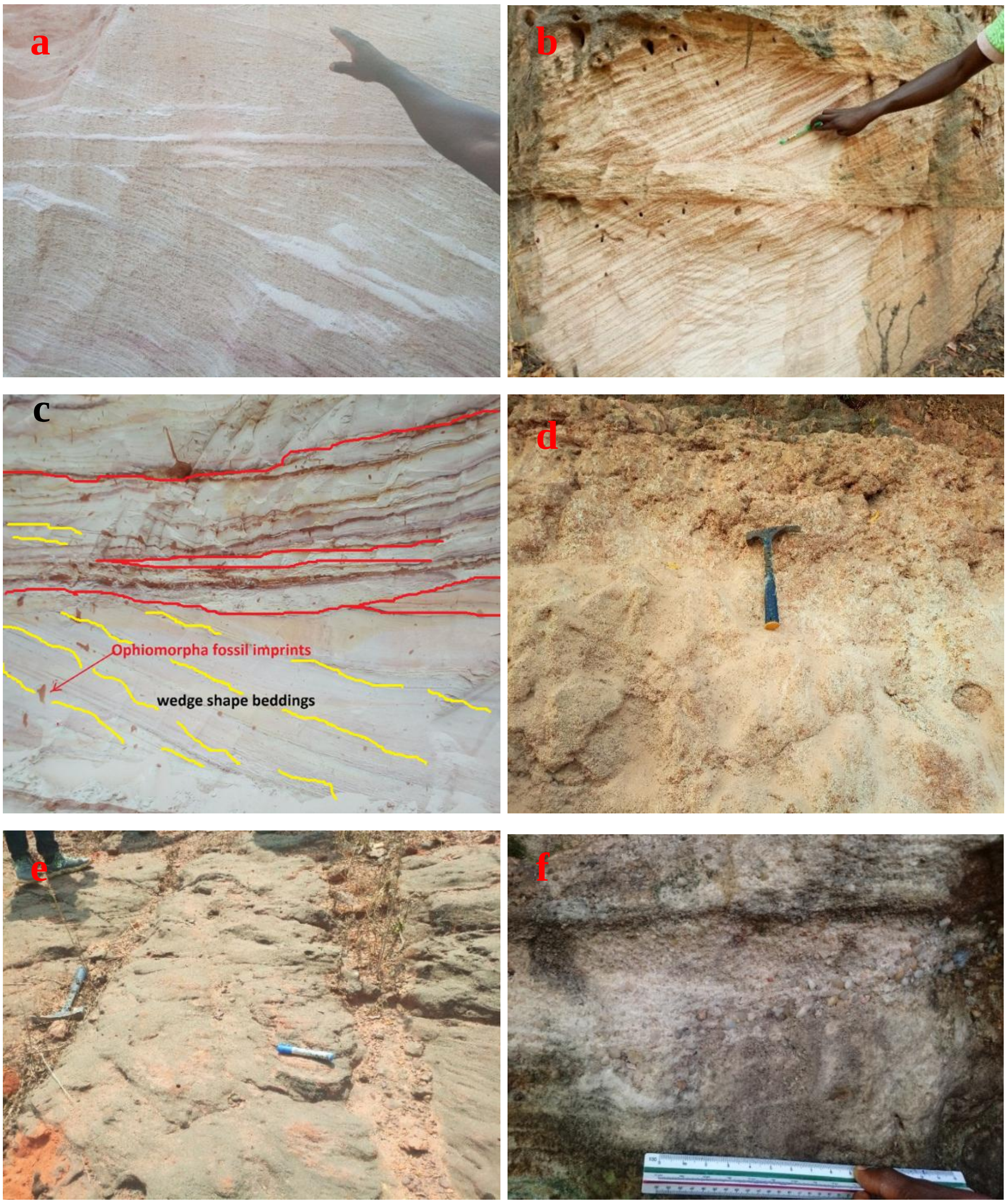

Fig. 14: Prospective reservoir rock outcrops in the Northern Anambra Basin. (**a**) Ajali Formation's medium-grained sandstone is visible at the quarry part of Iyale Hills, off the Anyigba-Ife route in Central Nigeria. (**b**) Section of the Ajali Formation, cross-bedded sandstone with regular grading at the foreset of the lamina is visible at the Ocheche River portion of Ocheche Cliff, Idah, Central Nigeria. (**c**) A quarry section in Iyale Hills, near Anyigba-Ife road, Central Nigeria, cross-bedded sandstone of the Ajali Formation display mud drape on foreset lamina (mud could operate as a baffle affecting reservoir quality). (d) A road cut section in Ochadamu hamlet, off Lokoja–Anyigba road, Central Nigeria, a unit of Ajali Sandstone that has been intensely bioturbed with *skolithos* and *Ophiomorpha* burrows is revealed. (e) Ripple laminated sandstone unit exposed at GRA Idah, Central Nigeria; (f) Ajali Formation pebbly

sandstone units exposed at Ocheche.

Fig. 15: Structural trap outcrop in the Northern Anambra Basin. (**a** and **b)** Along the Ajegu-Anyigba Expressway in Central Nigeria, the middle portion of the Mamu Formation displays an interval of shale, clay, and siltstones, as well as partially-developed growth faults and joints. (**c)** A well-developed growth fault in the Mamu Formation is exposed on the bank of the Ocheche River in Idah, Central Nigeria, and displaying intercalation of medium to coarse-grained, massive bedded and cross-bedded sandstones (notice the rollover structures on both the hanging wall and the footwall). (**d)** Agbenema village, Omala Local Government, Kogi State, Nigeria, showcases the partially weathered thick shale facies of the Mamu Formation, which exhibits a faulted block at the bottom level.

Fig. 16: Photograph of Road cut section of Nkporo/Enugu Shale exposed close to the overhead bridge, along Enugu-Onitsha Expressway about 200 meters from the head bridge (06° 28′ 09″N, 7° 28′ 17″ E), (a,b) the basal part of the Nkporo shale showing the thick shale and the laterized silt stone, (c) Road cut section of Mamu Formation exposed beside Enugu-Onitsha road, Enugu State (06° 28′ 13.7″N, 7° 27′ 8.55″ E), characterized by interbeds of siltstone, shale, coal, heteroliths, and clay, (d) Ajali Sandstone exposed in a quarry, along Enugu-Onitsha Expressway, 2km from Onyeama Mine (07° 26′ 00″ N, 06° 28′ 4″ E), characterized by fine to medium grain, friable, cross beddings (Planar, tabular, herringbone, flaser, wedge shape, etc.) and bioturbation (ophiomorpher and skolithos) structures (e) Nsukka Formation lateritic capping exposed close to

the overhead bridge, Enugu-Onitsha Expressway (06° 46′ 22″ N, 07° 26′ 32″ E, Elevation 480 m).

4.2 Outcrop Characteristics of Selected Formations in the Southeastern Anambra Basin

The Nkporo/Enugu Shale represents the basal stratigraphic unit in the Anambra Basin and is well exposed at a road cut along the Enugu-Onitsha Expressway, approximately 200 metres from the head bridge (06°28′09″N, 07°28′17″E; Elevation: 180 m). This Late Campanian to Maastrichtian prodelta deposit forms part of a transgressive-regressive cycle, deposited in a low-energy, funnel-shaped shallow marine environment transitioning into marshy conditions (Reijers & Nwajide, 1998). The exposure, measuring roughly 28 m thick, comprises grey fissile shale interbedded with lateritised siltstones. These alternating beds, increasing in siltstone frequency upwards, indicate a rapid shift in depositional energy. The sequence culminates in a 1 m thick brown-yellow siltstone unit. Laminations are common, and a NE–SW trending fault (30°) cuts across the beds. Fossil content includes ammonites, signifying marine influence (Fig. 16a,b, and c). Mamu Formation, exposed beside the Enugu-Onitsha Road (06°28′13.7″N, 07°27′8.55″E; Elevation: 216 m), the Mamu Formation reflects deposition during a regressive phase. It consists of alternating siltstone, shale, and coal layers, indicative of deltaic forest and floodplain settings. The basal siltstone (2.3 m) is dark grey, fine-grained, and compacted, overlain by a 3 m shale bed and a 0.5 m coal seam (Fig. 16d). Fossil leaves are preserved in the shale matrix, supporting its organic richness. A 4 m thick fine-grained shale atop the coal seam suggests an anaerobic environment conducive to organic matter preservation, followed by a 3 m clay band indicating a sudden depositional shift. Ajali Formation, observed 2 km from Onyeama Mine along the Enugu-Onitsha Expressway (07°26′00″N, 06°28′4″E; Elevation: 320 m), the Ajali Sandstone records a highstand regressive system. The 22 m thick quartz arenite is texturally and mineralogically mature, with cross-bedding structures such as herringbone, planar, and wedge-shaped types (Fig. 16e). These features, alongside trace fossils like *Ophiomorpha, Scoyenia*, and *Fungichnia*, reflect high-energy fluvial-tidal processes (Reijers & Nwajide, 1998). Nsukka Formation unit is exposed near the overhead bridge along the Enugu-Onitsha Expressway (06°46′22″N, 07°26′32″E; Elevation: 480 m). The Nsukka Formation, of Paleocene age, marks a renewed marine transgression and comprises organic-rich shales with potential for hydrocarbon generation, although limited maturity is reported in the Anambra region (Reijers & Nwajide, 1998). The reddish lateritic top (Fig. 16f) reflects oxidative weathering and iron leaching, possibly sourced from the Cameroun Highlands.

4.3 Elements of petroleum system

The fundamental components of petroleum systems include source rocks, traps, seals, and reservoir rocks. This paper utilizes outcrop studies to showcase the presence of potentially crucial elements that could enhance hydrocarbon prospectivity in the northern Anambra Basin.

4.3.1 Source rock presence and potential

Precursors of kerogen-organic matter, which is converted into hydrocarbons by prolonged exposure to high temperatures, are found in the source rock, which is where the early phases of oil and gas creation occur (Magoon and Dow 1994; Magoon and Beaumont 1999). The Mamu and Nsukka formations include coals and shales that could be used as source rock materials for the extraction of hydrocarbons in the northern Anambra Basin (Fig. 13a–f). According to Agagu (1978), the composition of these thick shales is rich in organic materials. According to research in petrology and organic geochemistry, coal layers in the Anambra Basin are important possible source rocks (Obaje et al. 2004). With huminites making up the majority and liptinites and inertinites in smaller amounts, the Mamu Formation (Campanian–Maastrichtian) coal deposits in the northern Anambra Basin have total organic carbon (TOC) contents of up to 60.8 weight percent, a mean hydrogen index (HI) of 364 mg HC/g TOC, vitrinite reflectance (Ro) ranging from 0.44 to 0.56%, and Tmax values between 430 and 433 °C. High molecular-weight n-alkanes are more common, pristane/phytane ratios are quite high, odd-over-even preponderance (OEP) is noticeable, C29 regular steranes are present in considerable amounts, and C28 levels are comparatively increased, according to biomarker analysis (Obaje et al. 2004). Together with maceral and biomarker data, the source rock data depicted by Obaje et al. (2004) on the modified Van Krevelen diagram shows source rock qualities that fall between fair and good. The coals may be immature or marginally mature, with the ability to generate both gas and oil, according to the vitrinite reflectance and Tmax results (Akande et al. 2012). According to earlier studies, the Mamu Formation's shales change from sub-mature to mature at deeper well sections that are farther from the basin's edges (Obaje et al. 1999).

4.3.2 Reservoir presence and potential

These components are part of the petroleum system, which is capable of collecting gas or oil. Because reservoir rocks have high porosity and permeability, fluids can be stored and released from them. According to Figure 14a–f, the Mamu, Ajali, and Nsukka formations contain sandstones, siltstones, and heterolithic intervals that make up the possible reservoir packages. There may be the most promising reservoirs in the Ajali Formation, which is mainly composed of fluviotidal sandstones. Since these sandstones include fine-to-medium grains that are sub-angular to rounded, Onyekuru et al. (2015) classify them as moderately well-sorted quartz arenites. When measured from surface outcrops, their permeability ranges from 7 to 55 darcy, and their interparticle porosity is significant (more than 21%). These sandstones have undergone bioturbation, which can either enhance or diminish the reservoir's quality (e.g. Jackson et al. 2013; Fig. 16). Additionally, the reservoir may become compartmentalized through the application of fluid barriers in the form of thin, laterally extensive clay bands, or lamina. Among the diagenetic processes affecting the sandstones of the Ajali Formation are moderate mechanical and chemical compaction, as evidenced by the frequency of point and line contacts and a relative absence of mineral overgrowths, and the authigenesis of kaolinite clay, which points to an early mesogenetic diagenetic stage (Onyekuru et al. 2015). Important reservoir possibilities, the sandstones of the Mamu Formation are very extensively spread. Fine-to-medium grains consisting of quartz arenites and feldspathic arenites make up their range, which is moderately to well sorted (Mode et al., 2016). A slight decline in the reservoir quality of these sandstones has been caused by the diagenetic changes, which include cementation (the overgrowth of quartz and feldspar), moderate-to-intense mechanical and chemical compaction (the dominant suture contacts between grains and quartz), and the conversion of many feldspars into clay minerals (Mode et al. 2016). According to a statistical investigation of the Mamu and Ajali Formations in many basin locations, over cementation has likely reduced the porosity of possible reservoirs in both formations (Obaje et al. 1999; Onuoha 2005). Using subsurface wellbore data, sequence stratigraphic correlation shows that these reservoir packages are often laterally continuous, except for regions where structural distortion has occurred (Dim et al. 2017, 2018).

4.3.3 Seal presence and effectiveness

The sealing integrity of a petroleum system is critical to hydrocarbon entrapment and preservation. In the northern Anambra Basin, intraformational shale units within the Mamu Formation and regionally extensive shales of the Nsukka Formation serve as the primary sealing lithologies (Fig. 14f). Both vertical and lateral hydrocarbon migration must be stopped by these seals. Geotechnical assessments show that Nsukka shales are more capable of withstanding ductile deformation under stress without breaking, as evidenced by their higher plasticity and hardness indices compared to Mamu Formation shales (Okogbue, 2012). This ductility is crucial for the creation of effective cap rocks that can withstand a variety of stress regimes (Downey, 1994). However, tectonic stress can lead to brittle failure of the Mamu Formation's shales, which often results in jointing and minor faulting that could compromise the seal's integrity (Fig. 15d; Okogbue, 2012). Despite these concerns, intraformational sealing potential can still occur, particularly when interbedded clay-rich intervals top reservoir-quality sandstones (Dim et al. 2018). Possible hydrocarbon entrapment processes linked to fault-bound traps and intraformational sealing are suggested by evidence of vertical columnar joints in coal seams and clay-smearing within faults (Fig. 9b; Fig. 15a–e). Broad lateral seals with a high retention capacity are provided by the thick, organic-rich shale packages of the Nsukka Formation, which were formed in low-energy lagoonal to offshore environments. Overall, the sealing facies' lithologic diversity, thickness, lateral continuity, and brittle and ductile deformation interact to significantly affect the basin's ability to retain hydrocarbons. These features highlight the potential for efficient entrapment and sealing in the northern Anambra Basin, particularly when combined with structural trapping systems (Obaje et al., 2004).

4.3.4 Entrapment mechanisms

The main means of entrapment in the northern Anambra Basin are structural and stratigraphic traps, which guarantee the retention of hydrocarbons and stop their upward or lateral escape. Growth faults are widely distributed across the Mamu and Ajali Formations, as shown by geological field data from significant outcrops and 2D seismic interpretations (Fig. 15a–e). These syn-sedimentary tectonic faults suggest dynamic depositional conditions that facilitated differential compaction and fault propagation, and they resemble structural types seen in the Niger Delta Basin (Abubakar, 2014; Dim et al., 2017, 2018). With their listric geometries, rollover anticlines, and drag structures, the growth faults provide traditional structural trap topologies that can localise hydrocarbon accumulations along fault planes and within related closures. Furthermore, stratigraphic entrapment is important, particularly in areas where lateral lithologic variations produce heterogeneities that facilitate hydrocarbon trapping or where reservoir-quality sandstones pinch out against impermeable shale facies. Stratigraphic traps are created in the Ajali and Mamu Formations by the interfingering of high-energy channel sandstones with finer-grained overbank or marine-influenced shale layers (Fig. 14). Additionally, fault-assisted entrapment is promoted by coal seams and clay smears along fault planes (Fig. 7b), which increase sealing potential. In the paralic sequences of the Mamu Formation, intraformational traps are common, especially where channelised sands are capped by clay-rich heteroliths (Dim et al., 2018). Overall, the northern Anambra Basin's substantial but little-studied petroleum prospectivity is highlighted by the interaction of growth fault systems, lateral lithological terminations, and vertically sealing shales, which sustain a variety of entrapment mechanisms.

4.3.5 Implications for hydrocarbon exploration

The integrated lithostratigraphic and sedimentological examination of outcrop exposures demonstrates the presence of all crucial elements of the petroleum system: source, reservoir, seal, and trap, underscoring the high exploration potential of the northern Anambra Basin. Field observations from the Ajali, Nsukka, and Mamu Formations indicate that there are well-developed sediment packages that may contain reservoirs and source rocks. Paralic and marginal marine facies are included in these packages (Figs. 3-15). The Mamu Formation, characterised by carbonaceous shale, coal seams, and fine-grained sandstones, provides both source and intraformational reservoir-seal pairings, while the Ajali Formation's thick, cross-bedded quartz arenites offer excellent reservoir quality with porosities >21% and permeability values of 7–55 darcy (Onyekuru et al., 2015). The Nsukka Formation has ductile, regionally broad shale sections that are highly flexible and produce excellent caprocks under a variety of stress regimes, ensuring sealing efficiency (Okogbue & Ugwoke, 2012). Growth fault systems, stratigraphic terminations, and intraformational heteroliths and shales all contribute to entrapment (Fig. 15d). Clay smearing and coal-seam jointing mechanisms further increase these traps, which are typically fault-assisted (Figs. 7b, 9b, 15d), indicating substantial hydrocarbon retention potential (Dim et al., 2018). Additionally, extensive accommodation for petroleum generation and entrapment is confirmed by basin-wide correlations using subsurface data, which show notable vertical thicknesses of up to 1200 m for the Mamu Formation, 600 m for the Ajali Sandstone, and 50 m for Nsukka shales (Onuoha & Dim, 2017). The northern Anambra Basin is positioned as a border zone for feasible hydrocarbon exploration in Nigeria due to the interaction of organic-rich source facies, clean reservoirs, and capable seals in this inland basin (Obaje et al., 2004; Akande et al., 2007).

4.4 Comparative Analysis of Outcrop Exposures in the Northern and Southeastern Anambra Basin, Nigeria

4.4.1 This study and Other Related studies proxies

Outcrop studies from the Anambra Basin provide critical insight into petroleum system elements and depositional evolution. Comparative observations between the northern and southeastern sectors reveal variations in lithofacies, sedimentary structures, and paleoenvironmental signatures that define hydrocarbon potential. In the Northern Anambra Basin, formations such as the Mamu, Ajali, and Nsukka are extensively exposed across locations like Ankpa, Anyigba, Idah, and Ocheche. The Mamu Formation is composed of strata that alternately consist of coal seams, siltstone, claystone, sandstone, and carbonaceous shale (Figs. 5–9). These are distinguished by sedimentary characteristics as bioturbation, burrowing, and hummocky cross-stratification that are typical of paralic to marginal marine environments (Adedosu et al., 2014; Adamu et al., 2018c). Structural features like expanding faults and fractures offer potential migration pathways and traps (Fig. 17). The northern Ajali Formation contains thick, friable to moderately cemented cross-bedded sandstones that exhibit bioturbation properties and reactivation surfaces (Figs. 10–13). These characteristics suggest fluvio-tidal processes and were seen at Iyale and Ocheche Cliff (Adamu et al., 2018a). Other markers of reservoir quality are the burrows of *Skolithos* and *Ophiomorpha* (Fig. 16). Hilltops (Iyale, Ogbogba) and road cuttings display the Nsukka Formation, which consists of layers of coal, shale, and siltstone with burrows and ripple marks that imply deposition in shoreface to lagoonal environments (Umeji & Nwajide, 2007).

The Nkporo/Enugu Shale, on the other hand, forms the exposed basal unit close to Enugu in the Southeastern Anambra Basin (Fig. 18a–c). Prodeltaic circumstances during a marine transgression are represented by the lateritized siltstone and grey shale containing ammonite fossils (Reijers & Nwajide, 1998). Compacted siltstone, coal, and organic-rich shale (Fig. 18d) are features of the Mamu Formation, which is exposed along the Enugu-Onitsha route and is indicative of deltaic forest habitats. High-energy fluvial-tidal processes are suggested by the quartz arenites in the Ajali Formation close to Onyeama Mine, which have planar and wedge-shaped cross-beds and biogenic traces like *Scoyenia* and *Fungichnia* (Fig. 18e). Observed close to the overhead bridge (Fig. 18f), the Nsukka Formation has lateritic capping and organic-rich shale, which are indicative of repeated transgression and oxidative weathering from hinterland sources. In conclusion, there are minor differences but similar facies successions in both regions. The southeastern basin has more mature marine transgression facies and organic-rich intervals, highlighting the regional variation in petroleum system development throughout the Anambra Basin, whereas the northern basin displays thicker coal seams and better-developed structural traps.

4.4.2 This study and Dim et al. 2018

This study showed a clear positive correlation of the geological and petroleum system elements for the exposed lithostratigraphy of the northern sector of the Anambra Basin examined and those reported by Dim et al. 2018 in the southeast flank. Apart from the presence of identifiable key components of the elements (source, reservoir, seal, and trap facies) in both segments, spiking lithofacies and structural features that show regional tectonosedimentary variations. Indicative of paralic to deltaic depositional environments, the Mamu Formation in the northern exposures is characterised by coal seams, bioturbated ferruginized facies, siltstone, interbedded claystone, and fissile shale (Figs. 3–7). Although the northern sites exhibit greater exposure of lateritized siltstones and thick, erosional surfaces suggestive of stronger subaerial influences, these facies are similar to the heterolithic intervals reported by Dim et al. (2018) at Onyeama and Iva Valley (SE Nigeria). However, northern exposures, especially around Ocheche and Iyale Hills, show more developed bioturbation and mud drapes (Figs. 8–11), suggesting fluctuating hydrodynamic regimes not as evident in Dim et al.'s southern records. The Ajali Formation in both regions exhibits prominent cross-bedding, planar and trough structures, and ripple laminations.

Also, the northern parts have better-preserved lateritized shale-claystone facies, even though both studies point to the coal-bearing Nsukka Formation as the source rocks. Both places have structurally visible anastomosing joints and typical faults that could act as migration pathways and traps. In contrast to the typical fault assemblages seen near the Four Corner and Onitsha road flyovers in the southeast, the northern basin exhibits well-developed rollover structures and faulted shale blocks (Fig. 15) (Dim et al., 2018). The northern exposures offer more structural and sedimentological information that could improve hydrocarbon prospectivity models throughout the Anambra Basin, even though the petroleum system components are generally consistent across regions.

5.0 CONCLUSION

This study provides compelling surface-based evidence for the presence and distribution of key petroleum system elements within the Northern Anambra Basin, Nigeria. Outcrop analyses confirm that the Mamu and Nsukka formations possess organic-rich coals and shales with favourable geochemical attributes for hydrocarbon generation, while the Ajali Formation sandstones demonstrate excellent reservoir potential with good porosity and permeability characteristics. Intraformational and regional seal rocks, particularly the ductile shales of the Nsukka Formation, appear to be appropriate for effective hydrocarbon trapping. The observation of growing faults, joint systems, and structural complexity, all of which suggest possible trapping mechanisms further supports the notion of a dynamic petroleum system in this region. These findings align with subsurface geophysical interpretations and previous geochemical studies, thereby strengthening the case for hydrocarbon prospectivity in Nigeria's inland basins. The clear facies successions, biogenic features, and lateral continuity of reservoir-seal pairs indicate a stratigraphically and structurally favourable setting. Consequently, the Northern Anambra Basin emerges as a highly prospective frontier for hydrocarbon exploration, warranting detailed subsurface evaluation and targeted drilling to validate the petroleum potential identified through this integrated surface geological framework.

6.0 ACKNOWLEDGEMENT

This paper is based on part of Nigerian National Petroleum Corporation NNPC Chair in Basinal Studies, Ibrahim Badamasi Babangida University, Lapai, Nigeria through the office of the Chair professor N. G. Obaje of blessed memory.

7.0 REFERENCES

1. Abubakar, M. B. (2014). Petroleum Potentials of the Nigerian Benue Trough and Anambra Basin: A Regional Synthesis, Nat Resour, 5, 25-58. http://dx.doi.org/10.4236/nr.2014.51005

2. Adamu, M.L., Rufai, A., Atabo, N.O. and Alege, T.S. (2017). Sedimentology and Depositional Environment of the Mid-MaastritchtianAjali Sandstone in Idah and Environs, Northern Anambra Basin, Northcentral Nigeria, *Journal of Applied Geology and Geophysics*, (6)1, 38-51.

3. Adamu, M.L., Hamza, H., Hamidu, I. and Obaje, N.G. (2018a).Sedimentology and Stratigraphy of the Campano-Maastritchtian Succession, Northeast of Idah Town, northern Anambra Basin, *DJOSTER*, 7(1), 127-153.

4. Adamu, L.M., Odoma, A.N., Ibrahim, M.M., Umar, U.O. and Alege, T. S. (2018b). Lineament Analysis and Structural Evolution of Ajaka and Environs, Northern Anambra Basin, *DJOSTER*, 7(2), 110-123.

5. Adamu M.L., Ayuba, R. and Alege, T.S. (2018c). Sedimentology and Depositional Environments of the MaastrichtianMamu Formation, Northern Anambra Basin, Nigeria, *Advances in Applied Science Research*, 9(2), 53-68.

6. Adamu L. M. and Ayuba R. (2019). *Guidelines for Geological Field Mapping of Basement and Sedimentary Terrain: With Examples from the Basement Rocks and Sedimentary Basins of Nigeria*, Ahmadu Bello University Press, Zaria, ISBN: 978-978-8543-63-3, 120pp.

7. Adamu, L.M., Obaje, N.G., Ngozi, O.P. and Umar, U.M. (2020). Integrated Geochemical and Multivariate Statistical Examination of Source Rocks in the Sokoto and Anambra Basins, Nigeria: Implications for Hydrocarbon Prospectivity, *Petroleum Science and Engineering*, 4(2), 39-50.

8. Adamu, L.M., Obaje, N.G., Ayuba, R., Kovona, M.T., Adesino, D.A., and Etukudo, N.J. (2022a). Litho-Bio Facies analysis and Systematic Paleontology of Sediments in Amansiodo-1 Well, Anambra Basin, Southeastern Nigeria.*Earth Sciences*, 11(3), 96-108. doi:10.11648/j.earth.20221103.16.

9. Adamu, L.M., Andongma, W.T., Jiriko, N.G., Mazadu, D.B., Shinkafi, F., and Mohammed, D.A. (2022b). A bivariate statistical analysis for coal exploration within

parts of the Anambra Basin in Nigeria, *Spatial Information Research, Springer*, https://doi.org/10.1007/s41324-022-00440-x

10. Adamu, L.M., Obaje, N.G., Adeoye, J.A., Oladimeji, R.G., and Yusuf, I. (2024). Trans-Saharan seaway connection between the south Atlantic and the Tethys Sea during the Coniacian – Turonian: Evidence from bibliographical synthesis, field mapping, and seismic interpretation, *Geosystems and Geoenvironment, Elsevier*, 3(2024) 100243.

11. Adedosu, T.A., Sonibare, O.O., Tuo, J., and Ekundayo, O. (2014). The occurrence of Lacustrine depositional setting in the Mamu Formation, Anambra Basin, Nigeria. Energy Sources Part A Recovery Utilization Environ Effects 36(4):374–382
12. Agagu, O.K. (1978). Geology and petroleum potentials of the Santonian to Maastrichtian sediments in the Anambra Basin, Eastern Nigeria. Ph.D. Thesis, University of Ibadan, Nigeria
13. Agagu, O.K., Fayose, E.A., and Petters, S.W. (1985). Stratigraphy and sedimentationin the Senonian Anambra Basin of eastern Nigeria. . *Journal of Mining and Geology, 22*, 25-36.

14. Akande, S.O., Ogunmoyero, I.B., Petersen, H.I., and Nytoft, H.P. (2007). Source rock evaluation of coals from the Lower MaastrichtianMamu Formation, SE Nigeria. J Pet Geol 30(4):303–324
15. Akande, S.O., Egenhoff, S.O, Obaje, N.G., Ojo, O.J., Adekeye, O.A., and Erdtmann, B.D. (2012). Hydrocarbon potential of Cretaceous sediments in the lower and middle Benue Tough, Nigeria: insights from new source rock facies evaluation. J Afr Earth Sci 64:34–47
16. Anyiam, O.A., Onuoha, K.M., and Jolly, B.A. (2015). Play fairway evaluation of the Anambra Basin, Southeast Nigeria. Arabian J Geosci 8:539–546
17. Dim, C.I.P., Onuoha, K.M., Okeugo, C.G., and Ozumba, B.M. (2017). Petroleum system elements within the Late Cretaceous and early Paleogene sediments of Nigeria's inland basins: an integrated sequence stratigraphic approach. J Afr Earth Sci 130:76–86
18. Dim, C.I.P., Mode, A.W., Okwara, I.C. (2018). Signatures of key petroleum system elements: outcrop examples from the Anambra Basin, Southeastern Nigeria. Journal of Petroleum Exploration and Production Technology 9:1615–1631. https://doi.org/10.1007/s13202-018-0589-2
19. Downey, M.W. (1994). Hydrocarbon seal rocks. In: Magoon LB, Dow WG (eds) The petroleum system: from source to trap, vol 60. American Association of Petroleum

Geologists Memoir, Tulsa, pp 159–159

20. Fatoye, F.B., and Yomi, G.B. (2013). Appraisal of the Economic Geology of Nigerian Coal Resources. *Journal of Environment and Earth Science, 3*(11).
21. Guiraud, R. and Bosworth, W. (1997). Senonian Basin Inversion and Rejuvenation of Rifting in Africa and Arabia: Syn- thesis and Implications to Plate-scale Tectonics," *Tectonophysics,* 282(1-4), 39-82. http://dx.doi.org/10.1016/S0040-1951(97)00212-6
22. Jackson, C.A., Mode, A.W., Oti, M.N., Adejinmi, K., Ozumba, B.M., Osterloff, P. (2013). Effects of bioturbation on reservoir quality: an integration in reservoir modeling of selected fields in the Niger delta petroleum province. NAPE Bull 25(1):29–42
23. Ladipo, K.O. (1988). Paleogeography, sedimentation and tectonics of the upper Cretaceous Anambra Basin, southeastern Nigeria. J Afr Earth Sci 7(5–6):865–871
24. Magoon, L.B., and Beaumont, E.A. (1999). Petroleum systems. Chapter 3 in exploring for oil and gas traps. In: Beaumont EA, Foster NH (eds) AAPG treatise of petroleum geology. Handbook of petroleum geology, AAPG, Tulsa, pp 1–3
25. Magoon, L.B., and Dow, W.G. (1994). The petroleum system: from source to trap. Am Assoc Pet GeolMem 60:655
26. Mode, A.W., Anyiam, O.A., Anigbogu, E.C. (2016). The effect of diagenesis on reservoir quality of Mamu Sandstone, Anambra Basin, Nigeria. J GeolSoc India 87:583–590
27. Nwajide, C.S. (2013). Geology of Nigeria's sedimentary basins. CSS Bookshops Limited, Lagos, p 565
28. Nwajide, C.S., and Reijers, T.J.A. (1996). Geology of the southern Anambra Basin. In: Reijers TJA (ed) Selected chapters on geology. SPDC, Warri, pp 133–148
29. Obaje, N.G., Ulu, O.K., and Petters, S.W. (1999). Biostratigraphic and geochemical controls of the hydrocarbon prospects in the Benue trough and Anambra basin, Nigeria. Niger Assoc Pet Explor Bull 14:18–54
30. Obaje, N.G., Wehner, H., Scheeder, G., Abubakar, M.B., and Jauro, A. (2004) Hydrocarbon prospectivity of Nigeria's inland basins: from the viewpoint of organic geochemistry and organic petrology. Am Assoc Pet Geol Bull 88:325–353
31. Obaje, N.G., (2009). Geology and Mineral Resources of Nigeria. *Springer Dordrecht Heidelberg London New York*, 221pp.
32. Obaje, N.G., Adamu, L.M., Umar, U.M., Umaru, A.O., and Okafor, P.N. (2020): Geochemical and Geostatistical Assessment of Cretaceous Coals and Shales in Some Nigerian Sedimentary Basins for their Hydrocarbon Proness and Maturity Levels, *African Journal of Engineering and Environment Research*, 1(2), 2-16.

33. Odumoso, S., Oloto, I., and Omoboriowo, A. (2013). Sedimentological and depositional enviroment of the Mid-MaastritchtianAjali Sandstone, Anambra Basin, Southern Nigeria. . *Int J Sci Technol*, *3*(1), 2224–3577.

34. Odumodu, C.F.R. (2014). Ichnology and lithofacies analysis of the Campano–MaastrichtianMamu Formation in the northern parts of the Anambra Basin, Nigeria. Int J Geol Earth Environ Sci 4(3):130–137

35. Okogbue, C.O., and Ugwoke, T.S. (2012). Inferring hydrocarbon migration and sealing potentials of some shales of the Anambra Basin (Southeastern Nigeria) from their paragenesis and geotechnical index properties. GeotechGeolEng 30:1249–1260

36. Onuoha, K.M. (2005). A Close Look at the Petroleum Potential of the Anambra Basin: Inputs from Geophysics and Geo- history, In: C. O. Okogbue, Ed., *Hydrocarbon Potentials of the Anambra Basin*: *Geology*, *Geochemistry and Geohistory Perspectives*, Great AP Express Publisher Limited, Nsukka, 83-110.

37. Onuoha, K.M., and Dim, C.I.P. (2017). Developing unconventional petroleum resources in Nigeria: an assessment of shale gas and shale oil prospects and challenges in the inland Anambra Basin. In: Onuoha KM (ed) Advances in petroleum geoscience research in Nigeria, Chapter 16, 1st edn. University of Nigeria, Nsukka, pp 313–328

38. Onyekuru, S.O., Opara, K.D., Iwuagwu, C.J., and Opara, A.I. (2015). Diagenetic study of sandstone sediments in parts of Anambra and Afikpo Basins, Southeastern Nigeria. FUTO J Ser 1(2):316–331

39. Reyment, R.A. (1965). Aspects of the geology of Nigeria. *Ibadan. Univ. Press*, *Ibadan*, *Nigeria*, 145pp.

40. Udo, I.G., Etukudo, N.J., Abia, U.B., and Ibanga, I.M. (2020). Facies analysis and depositional environment of conglomeritic deposits in the northern part of the Niger Delta Basin, Nigeria, IOSR Journal of Applied Geology and Geophysics, 8(3), 11-30.

41. Udo, I.G., Udofia, P.A., Etukudo, N.J., and Adesina, D.A. (2023a). Paleoenvironmental Interpretation of the exposed section of the Benin Formation in Southeastern part of the Niger Delta Basin, Nigeria: A pebble morphometric approach, IOSR Journal of Applied Geology and Geophysics, II(3), 12-19.

42. Udo, I.G., Udofia, P.A., Etukudo, N.J., and Ibanga, I.M. (2023b). Sedimentary facies analysis of sandstone member of the Imo Formation in Northern part of the Niger Delta Basin, Nigeria, The International Journal of Engineering and Sciences, 12(6), 25-37

43. Umeji, O.P., and Nwajide, C.S. (2007). Age control and designation of the standard stratotype of Nsukka Formation of Anambra Basin, southeastern Nigeria. J Min Geol 43(2):147–166
44. Yunusa, L.J., Adamu, L.M., Umaru, A.O. and Alege, T.S. (2020a). Quality Assessment and Physical Characteristics of Awo-Akpali coal, Northern Anambra Basin, Nigeria: Insight from Ultimate Analysis and Field Studies, *Minna Journal of Geosciences (MJG)*, 4(2), 180-195.
45. Yunusa, L.J., Bolarinwa, A.T., Adamu, L.M., Alege, T.S. and Umaru, A.O. (2020b). Applicability and Resource Estimation of Awo-Akpali coal, Ankpa Sub-Basin, Northcentral Nigeria, *Minna Journal of Geosciences (MJG)*, 4(2), 209-224.
46. Yusuf, I., Obaje, N.G., Adedosu, T.A., Adeoye, J.A., Adamu, L.M., Tsado, F., and Gana, E.Y. (2023). Geology, Sedimentological and Hydraulic Conductivity of Ajali Potential Reservoir Sandstone Exposed Around GRA in Idah, Northern Anambra Basin, *FUDMA Journal of Sciences*, 7(6), 290-297.
47. Zaborski, P.M. (2000). The Cretaceous and Paleocene Transgressions in Nigeria and Niger, *Journal of Mining Geology*, 36(2), 153-173.