Petrographic and Structural Implications on Petroleum System in Igumale-Nsukka Area in Relation to Anambra Graben, Nigeria

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Abstract—*The Mamu and Nsukka Formations consist of alternating sandstones, sandy shales and mudstones with interbedded coal seams. The formation is underlain by the Campanian Enugu/Nkporo Shales, and overlain by the Ajali Sandstone and Nsukka Formation. Four main stratigraphic units belonging to the Enugu Shale, the Mamu Formation and the Ajali Sandstone were recognized. These units are the Enugu Shale, the Lower and Upper Mamu and the Ajali Sandstone. The Enugu Shale is the oldest unit which forms the base of the sequence was into subunits; carbonaceous shale, grey shale and sandy shale. The Mamu Formation succeeded the Enugu Shale and two members of this formation; lower and upper Mamu are recognized. The aim of this study is to examine the petrography of the Enugu Shale, the Mamu Formation and the Ajali Sandstone, investigates the structural features within the formations and to highlights their importance in relation to petroleum system in the area. The Ajali Sandstone overlain the Upper Mamu and consists of whitish to pinkish red, poorly consolidated medium grained sandstones. It is well cross-bedded and contains plant impression, and burrow-fills as ichno-fossils. The presence of predominant monocrystalline quartz grains in quartz arenite and the absence of feldspar in the sandstone are evidences of long transportation, mineralogical and textural maturity of the sandstones. These areas have high economic potentiality for hydrocarbon accumulation. A more detailed exploration is required in the study area and even the entire Anambra Basin in order to know about the extent of hydrocarbon reserves in these areas.*

Keywords: Shale, sandstone, grain-sizes, structures, petroleum, Anambra Basin.

I. INTRODUCTION

The studied area is bounded by longitudes 7°30´E and 7°38´E and latitudes 6°45´N and 6°51´N. It is located in the north west of Igumale and lies northwest of Nsukka. The area which covers 40.5km2 lies within the Anambra Basin and includes the following towns, Ehalumona, Mbu, Imilike-Agu, Ogboduaba, and a part of Opi-Agu and Ezimo (Fig. 1). The area is accessible by roads and footpaths. The main access routes are the Eha-Alumonah-Mbu-Ikemu trunk C road, the Obolo-afor-Ogboduaba-Mbu-Enugu new road and Eha-Alumona-Agu –Umabor-Opi road.

Many areas of Southern Nigeria including the studied area were first investigated by Shell D'Arcy during their early stages of oil prospecting in Nigeria from 1938-1957. "Simpson [1] studied the Nigerian coal fields and the general geology of parts of Onitsha, Owerri and Benue provinces and observed that the occurrence of Nigerian coal seams were mainly within the Mamu Formation". "De Swardt and Cassey [2] show the structure and stratigraphy of the Nigerian coal fields, and observed that Nigerian coal is sub-bituminous". "Reyment [3] attempted a biostratigraphic correlation of the stratigraphic units of the southern Nigerian sedimentary basins". On the basis of abundant index fossils such as pelecypods, ammonites and foraminifera, he dated the Eze-aku shales (lower Turonian, the Nkporo shales (Campanian) which are lateral equivalent to Enugu shales while the Mamu, Ajali and Nsukka formations are Maastrichtian (Fig. 2).

"Short and Stauble [4] noted that there were three main sedimentary cycles in the southern Nigerian sedimentary basins. The first (Albian to Santonian) was restricted to Benue trough". The second (Campanian-Eocene) cycle filled the Anambra Basin (to which the studied area belongs) and the Afikpo syncline, and third initiated the formation of the modern Niger Delta. They also recognized that there was uplift during the Paleocene-Eocene, which resulted in the erosion of the rejuvenated Abakaliki anticlinorium, the Anambra Basin and Afikpo syncline.

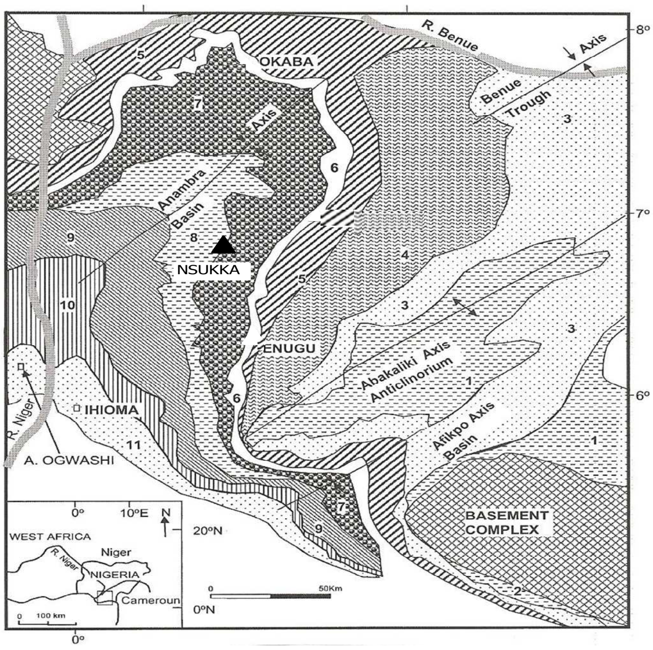


Fig. 1: Generalised geological map of the SE Nigeria (boxed areas of inset) showing the location of the coal deposits. Numbers indicate Cretaceous and Tertiary formations shown as follows 1. Asu River Group; 2. Odikpani Formation; 3. Eze-Aku Shale; 4. Awgu Shale; 5. Enugu/Nkporo Shale; 6. Mamu Formation; 7. Ajali Sandstone; 8. Nsukka Formation; 9. Imo Shale; 10. Ameki Formation and 11. Ogwashi-Asaba Formation (modified from [5]).

“Murat [6] studied the stratigraphy and paleogeography of Cretaceous and lowers Tertiary in the Southern Nigeria and noted that the sedimentary basin of Southern Nigeria was controlled by three major tectonic phases”. “Burke et al. [7] recognized that sediments of the second cycle were derived from the folded Abakaliki anticlinorium”. “Nwachukwu [8] in his study of tectonic evolution of the southern part of Benue trough noted that a slight tectonic movement probably took place during the Cenomanian”. “Uzuakpunwa [9] in his discussion on the tectonic implication of the Abakaliki pyroclastic, suggested a pre-Albian movement along the NE-SW trending fault system resulting in the formation of rift like Benue trough”.

“Hoque [10] in his study of the textural significance and petrographic attributes of several tectonic controlled Cretaceous sediments in Southern Nigeria found that the sediments of the first sedimentary cycle are feldspartic”. He also noted that those of the second cycle (found mainly within the Anambra Basin which includes the studied area) are devoid of feldspar. “Uzoegbu et al. [11] more recently proposed a stratotype for the Nsukka Formation when they noticed the generalization of similarity between the Mamu and Nsukka formations”. This paper aims to examine the petrographic properties of the Enugu Shale, the Mamu Formation and the Ajali Sandstone, investigates the structural features within the formations and to highlights their importance in relation to petroleum system in the area.

II. REGIONAL STRATIGRAPHIC SETTING

Sub-bituminous coals are restricted to the Maastrichtian Mamu and Nsukka Formations which crops out in long narrow ridges in the NE–SW trending Anambra Basin (Fig. 1). The Mamu and Nsukka Formations consist of alternating sandstones, sandy shales and mudstones with interbedded coal seams. The formation is underlain by the Campanian Enugu/Nkporo Shales (lateral equivalents), and overlain by the Ajali Sandstone (Middle Maastrichtian) and Nsukka Formation (Upper Maastrichtian to Danian) (Fig. 2). Five sedimentary units are recognized in the Mamu Formation in the Enugu area, where the thickest exposed section (approximately 80 m) occurs [1], [3], [12]. From the base, the units consist of (i) a basal shale or sandy shale, (ii) sandstones with occasional shale beds, (iii) carbonaceous shales, (iv) coals and (v) sandy shales. The Nsukka Formation has well exposed section at Iyinzu in Ezimo area with thickness of about 55 m. The succession is paralic as demonstrated by the alternating marine and continental facies, and is considered to represent part of the “third marine cycle” in southern Nigeria, [4], [13], [14]. Sediments of the third marine cycle were mainly deposited in Campanian – Maastrichtian times in the Anambra and Afikpo Basins (Fig.1). These two post-Santonian basins were formed as successors to the Benue Trough, where deposition of the first and second marine depositional cycles took place in Albian – Santonian times (Figs. 1 and 2). The third-cycle sediments were deposited during the initial growth of the proto-Niger Delta in the Late Cretaceous [4]. An Early Paleocene transgression led to the termination of the proto-Niger Delta and the deposition of Imo Shale, which was succeeded by the regressive phases of the Ameki and Ogwashi Asaba Formations.

III. MATERIALS AND METHODS

Four stratigraphic units belonging to the Enugu Shale, the Mamu Formation and the Ajali Sandstone were mapped. These stratigraphic units are the Enugu Shale, Lower Mamu, the Upper Mamu and the Ajali Sandstones (Fig. 1). The Enugu Shale and the lower Mamu Formation could be subdivided into sub-units (Table 1).

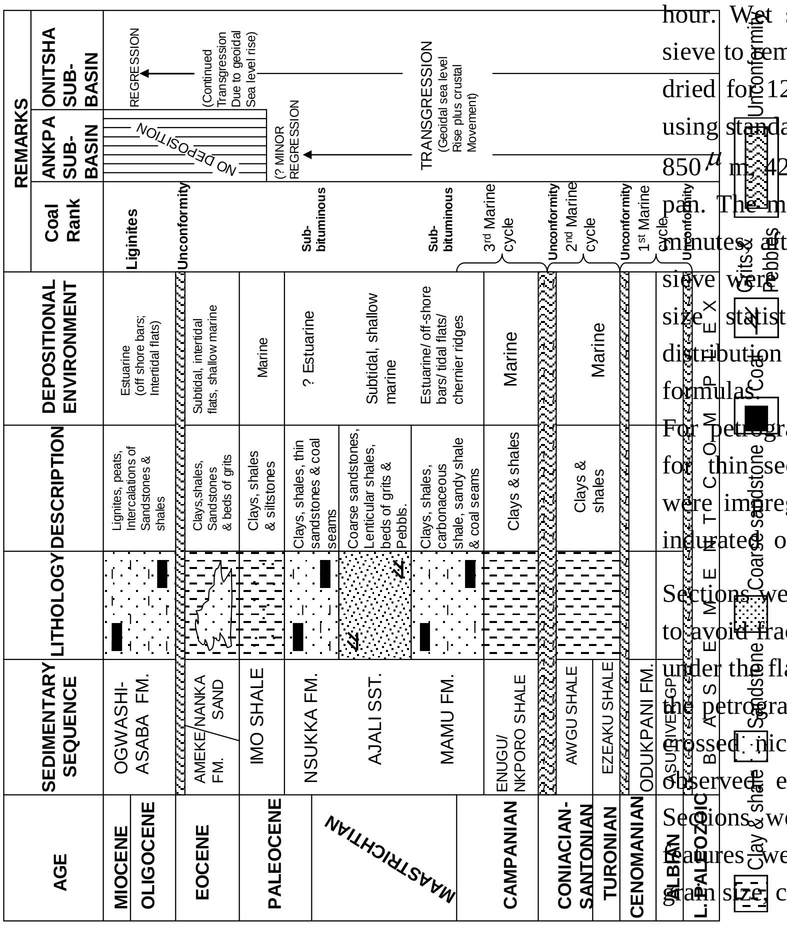


Fig. 2: The stratigraphy of the Anambra Basin southeastern Nigeria (modified after [13], [18]).

A detailed geological survey of mapping, measuring and studying in details the litholgic units, rock types and topography of the area were carried out. The measurement of sections was done simultaneously with sampling. Six outcrop sections were studied and sampled. Some features that were of particular interest were noted. For the detailed geological survey, field instruments used include silver compass, measuring tape, geologic hammer, camera, haversack, field notebook and global positioning system (GPS). Seven samples were selected for sieve analysis.

The samples were disaggregated into individual grains by the use of ceramic pestle and mortar, and about 126.0gm of each sample were then soaked in hydrogen peroxide for 12 hour. Wet sieving was carried out using 63-μm mesh sieve to remove the clay/mud fraction. Each was then oven dried for 12 hours to remove moisture content and sieved using standard sieve opening of 3.35mm, 2.36 mm, 1.18mm 850μm, 425μm, 300μm, 212μm, 106μm, 63μm and pan. The mechanical sieve shaker was switched on for 15 minutes, after which the segregated grains retained in each sieve were collected and weighed and then used for grain size statistical analysis. The analysis of grain size distribution was carried out for Ajali Sandstone, using [17] formulas.

For petrographical analyses eleven samples were selected for thin sectioning. Friable and unconsolidated samples were impregnated with araldite and Canada balsam while indurated ones were simply cut and mounted on slides. Sections were cut and polished to final thickness of 30μm to avoid fracturing and plucking. The slides were examined under the flat stage of a petrological microscope to estimate the petrograghic parameters under plane polarized light and crossed nicols. Sedimentary structures in outcrops were observed, examined, studied and noted. Lithostatigraphic Sections were measured from base to top. Interesting features were noted and photographed. Beds thickness, grain size, colour, estimated sorting were all noted.

Table 1: Lithostratigraphic succession established in the studied area (modified from [2]).

Age	**Formation**	**Member**	**Thickness (m)**	**Descriptions**

Upper Maastrichtian	Ajali Sandstone	Ajali Sandstone	400	Medium to coarse grained, poorly consolidated, friable with whitish mudstone bands at various horizons. The sandstone is typically cross-bedded.
Lower Maastrichtian	Mamu	Upper Mamu	100	Medium to fine grained, Friable white sandstone.
		Lower Mamu	200	Alternation of grey shales, and sandy shale which are thinly laminated and occasionally carbonaceous shale with coal seams at various horizons in rhythemic manner.
Campano-Maastrichtian	Enugu Shale		150	Soft dark grey to bluish carbonaceous shales. Nodular concretions are present in these shales and the shales are thinly laminated with mudstones.

IV. RESULTS AND DISCUSSIONS

Petrography

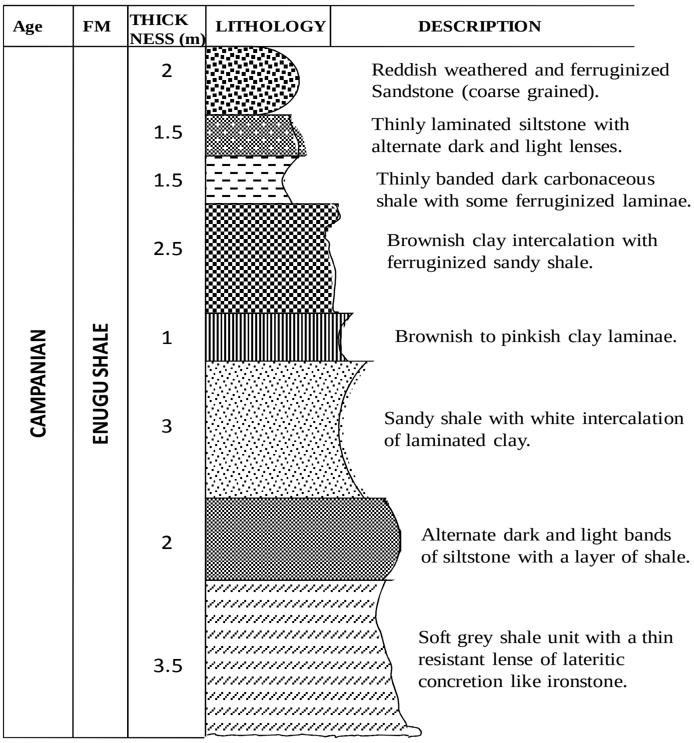
The Campano-Maastrichtian Enugu Shale with an approximate thickness of 150 m exposed at Imilike Agu as a type section. “Simpson [1], [3] described the Enugu Shale from its area in Asata and Obweeti stream valley within Enugu area”. The Enugu Shale which underlies the plain east of the Enugu escarpment in the mapped area covers about 40% of the area. It consists of predominantly soft, dark grey blue carbonaceous shales and sandy shale which alternate with siltstones and occasional bands of mudstones intercalation.

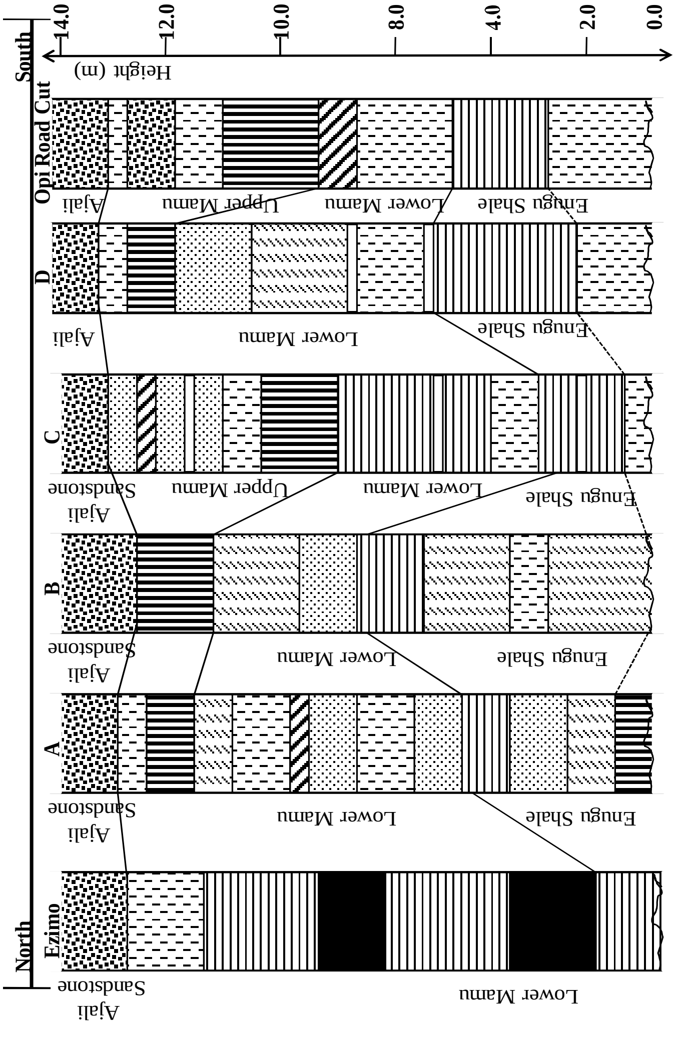
Enugu Shale

The studied area the lithologic unit of the Enugu Shale can be subdivided into three main subunits as (a) Sandy shale, (b) Grey shale and (c) Carbonaceous shale.

Carbonaceous Shale: An exposure of this subunit is recognized along the channel of the Vava stream at Imilike-Agu. It comprises of dark soft carbonaceous shales which are thinly laminated (Fig. 3). The shales are dark blue with nodular concretions and potholes at the base with intercalation of clay which alternate with siltstone [18]. At the top it is weathered to ferruginized sandstone (Fig. 4). Along Opi new road which about 3km outside the studied area a beautiful exposure of this subunit was recognized. This subunit has a prominent set of vertical joints trending NE-SW and has dip of 4^o to 6^o. The strikes range from 165^o to 230^o.

Grey Shale: The type sections of this subunit in the studied area were recognized along the channels of Ofianzu and Isiogene-Onu streams at Mbu and at Eha-ndiagu along the channels of Omeme and Iyi-akwa streams. The grey shales alternate with mudstones and fine sandstones. The grey shale is commonly found overlying the carbonaceous shale in the most of the outcrops studied, and also has nodular concretions. This shale gradually graded into sandy shale upwards and in some places it is weathered to reddish brown coarse sandstone or ferruginized sandstone and the top of which is capped with laterites (Fig. 4E).





The grey shales are characteristically fissile and split into thin flexible flakes of various sizes. The colours of dark carbonaceous shale and grey shale are due to the quantity of organic matter or oxidation state of iron in the rock [11], [19], [20], [21], [22], [23], [24]. The dip amount ranges from 4o to 5o and dip direction is between 220o to 280o. The grey shale has vertical joints which trend in NE-SW direction.

Petrology

The carbonaceous Enugu shales are a mixture of silt-size quartz and clay minerals which appear to be floating in dense mudstone matrix (Fig. 5). Quartz grains are more abundant than clay minerals and shales are generally silty. The fine quartz crystals are sub-angular to subrounded and scattered within the clay matrix. Dark minerals which are colourless under crossed polar are present and carbonaceous matter mainly plant fragments are observed. Sandy shale: The sandy shale forms the upper part of the grey shale in the studied area and consists of alternating thinly laminated shales, very fine sandstones which are whitish to brownish in colour with thin bands of clay intercalations (Fig. 6). The top of this sandy shale in weathered to reddish brown and is capped with laterites. Varve structures are common to the sandy shales. Beautiful exposures of this subunit are recognized along the new road cut at Mbu, Ogboduaba and along the channel of Ofianzu stream. The sandy shale contains plant debris and bioturbation structures in some places. It has vertical joints trending in NE-SW. The dip amount ranges from 2o to 4o and the dip direction is 340 azimuths.

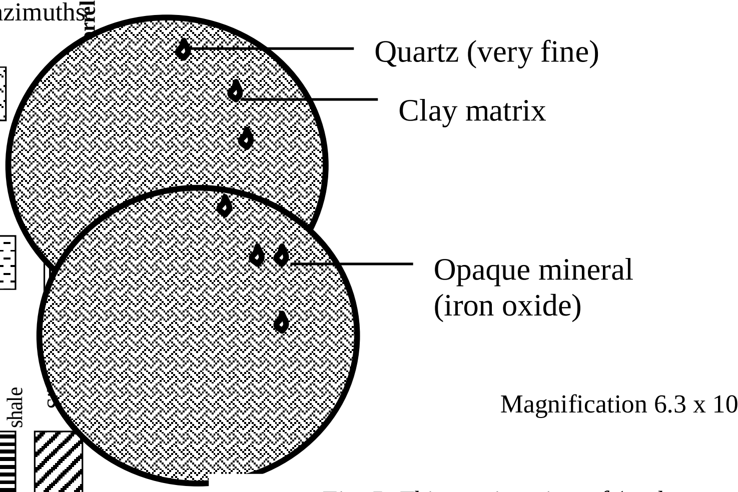


Fig. 5: Thin section view of (carbonaceo

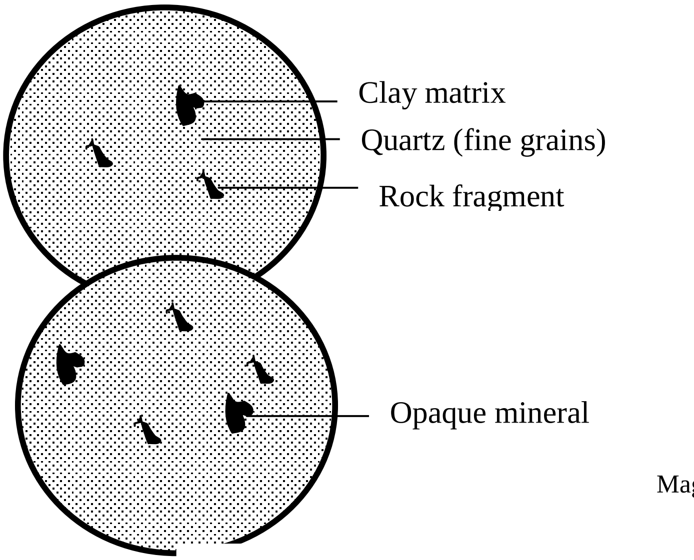


Fig. 6: Thin section view of Mamu sand

Microscopic studies show that sandstone consists of subangular to subrounded quartz floating in the matrix (Fig. 6). The grains are equant to subequant. The modal analysis of the framework elements shows; Quartz (85%), Matrix (10%) and Opaque (5%). The quartz grains contain monocrystalline quartz (95%) and polycrystalline quartz (5%). The sandstone is quartz arenite [11], [20], [21], [22], [23], [24], [25].

Environment of Deposition

The occurrence of plant remains, concretions, shale casts, varve structures, thin lamination and freshwater associated with these subunits of the Enugu Shale suggests deposition under shallow marine conditions. The gradation from carbonaceous shale to fine and siltstone also suggests open or shallow marine environment.

Lower Mamu: The lower Mamu covers about 30% of the studied area and three subunits of this formation are recognized; Carbonaceous shale, Grey shale and Sandy shale (Fig. 7).

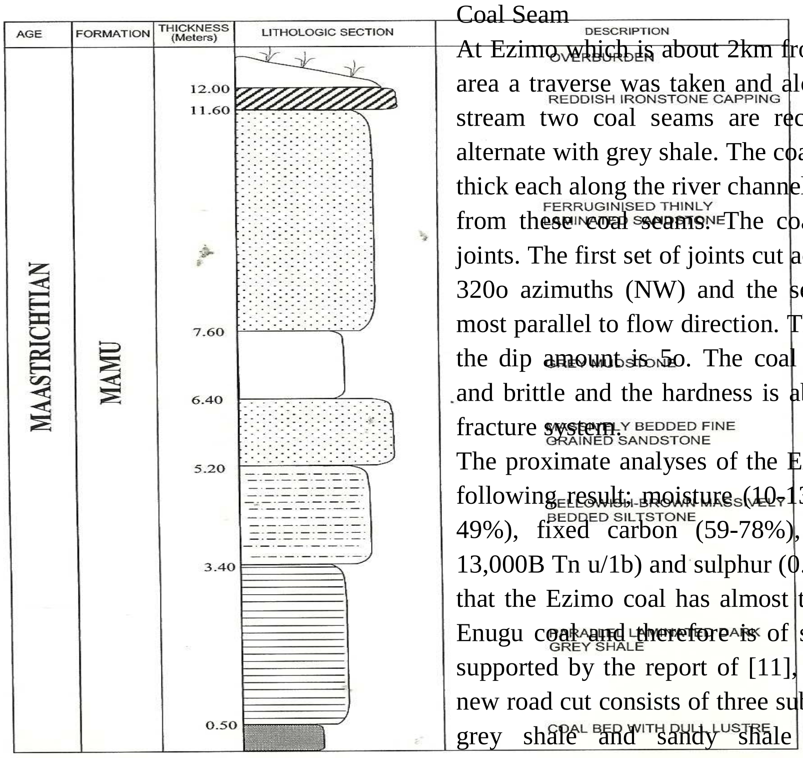


Fig. 7: Lithologic profile of lower Mamu formation.

Carbonaceous shale: This subunit has beautiful outcrops at the sources of Igbogbo stream, Iyi-Agu Orba and along channel Iyi-Vava at Anyazulu Umabor. The shale is dark thinly laminated with occasional thin bands of clay intercalations towards the upper part [18]. Each lamination is about 2cm. Varve structures and concretions are found in some of places. The shale is commonly found in very deep valley of the streams at the lower slope of Enugu escarpment. In some places this subunit delineates the contact between the Ajali and lower Mamu

Grey shale and sandy shale: The grey shale consists of thinly laminated dark grey shale alternating with mudstone, and fine sandstone and gradually graded into sandy shale at upper part. The grey sandy shale is highly fissible and contains plant impressions and bioturbation structures. The sandy shale at the upper part of the grey shale alternates with fine sandstone and siltstone and occasionally poorly laminated in some places. The sandy shale is highly weathered to reddish brown and the sandstone is ferruginized. The upper part is commonly capped with laterites. In the studied area the grey sandy shale has excellent exposures at Omeme stream and Ugene stream.

Coal Seam

At Ezimo which is about 2km from the north of the studied area a traverse was taken and along the channel of Iyi-nzu stream two coal seams are recognized. The coal seams alternate with grey shale. The coal seams exposed are 1.5 m thick each along the river channels and waterfalls developed from these coal seams. The coal has two set of vertical joints. The first set of joints cut across the stream and trends 320o azimuths (NW) and the second set trends 340o, all most parallel to flow direction. The strike is about 225o and the dip amount is 5o. The coal is generally black, friable and brittle and the hardness is about 2.5. It has a splintery fracture system.

The proximate analyses of the Ezimo coal by [2] show the following result; moisture (10-13.6%), volatile matter (39-49%), fixed carbon (59-78%), calorific value (10,000-13,000B Tn u/1b) and sulphur (0.5-%). This analyses shows that the Ezimo coal has almost the same quality as that of Enugu coal and therefore is of sub-bituminous class. This supported by the report of [11], [26], [27], [28]. The Opi new road cut consists of three subunits; carbonaceous shale, grey shale and sandy shale without coal seams as recognized in the studied area.

The occurrence of coal seams at Ezimo and the absence of these in the lower Mamu in the studied area and along Opi new road cut are evidence that Ezimo coal seams are stratigraphically lower than the studied area and Opi new road cut (Fig. 4).

Coal Depositional Environment

The abundance of carbonaceous shale in the studied area and coal seam at Ezimo, all in the lower Mamu suggests non-marine or swamp deposits. The regressive phase in the second sedimentary fill up of Anambra Basin is marked by the development of paralic sequence of Mamu Formation which is overlain by continental sequence of the Ajali Sandstones [3], [6].

Upper Mamu Member: The upper Mamu formation covers about 10% of the studied area and is made of only one unit. In the studied area this unit is not well exposed but it has an excellent outcrop along Opi road cut (Fig. 4). In this unit the main rock type is whitish to grey sandstone. The sandstone is very fine grained, friable and thinly laminated with thin bands of mudstone intercalation. Each lamination is about 1cm thick. Towards the base the lamination increases in thickness for about 3cm and the sandstones became coarser [11], [20], [21], [22], [23], [24]. These grades upwards to medium and fine grained. This shows fining upward sequence. This unit is highly burrowed and bioturbation structures which are evidence of ichnofossils were found.

Sieve analysis of the sandstone shows that it is negatively skewed; leptokurtic in grain size distribution and with mean size between 2.50-3.40 ø (Table 2) and the histogram plot show a unimodal distribution (Fig. 8).

Ajali Sandstone: “Simpson [1], [3], [29] described the Ajali Sandstone from its type areas along Ajali river and Nkpologu in Nsukka area. It occupies about 15% of the studied area and is found on the western margin of the area”. This is the youngest formation and it overlies the Mamu Formation. It has beautiful outcrops at Ugwu-Ikwube in the studied area and along Opi road cut. At Ugwu-Ikwube this outcrop has a well developed fascinating cave system. The sandstone is characteristically friable poorly consolidated, white to pinkish colour, iron stained with thin bands of white mudstones. At Ugwu-Ikwube the sandstone is typically cross-bedded on small scale (Fig. 9). The grains grade from medium to fine grain upwards and the beddings are massive at the base and became thinly laminated upwards.

The angle of inclination of the forest laminae with the underlying major bedding planes ranges from 20o to 25o. The cross-beds are of planar tabular form and vary in thickness from 5cm to 30cm. The bounding planar tabular cross-beds are planar surfaces of erosion or non-deposition. Analysis of the 25 measurements of the dip directions of cross-beds from two locations within the studied area shows that the mean dip azimuth is 248.08o (SW) with a standard deviation of 55.09o (Table 3). Rose diagram plot shows easterly to northwest mean current azimuth.

Sieve analysis of the sandstone shows that it is well sorted and skewness is positive and ranges from nearly symmetrical to leptokurtic grain size distribution (Table 4). Histogram plots show bimodal distribution between 1.0-1.50 ø (Fig. 10). The mechanical analysis of coarse sandstone shows that the sandstone is poorly sorted, negatively skewed leptokurtic and slightly bimodal.

Table 2: Seive analysis for white sandstone of upper Mamu.

Phi (ø)	Wt. Retained on Seive	Corrected wt.	Cumulative wt.	Cumulative wt. %	Weight (%)
0.0-5.0	0.6	0.6	0.6	1.1	1.1
0.5-1.0	2.4	2.4	3.0	5.6	4.5
1.0-1.5	3.2	3.2	6.2	11.5	5.3
1.5-2.0	2.9	2.9	9.1	16.8	5.9
2.0-2.5	4.0	4.0	13.2	24.2	7.4
2.5-3.0	8.3	8.4	21.6	39.7	15.5
3.0-3.5	19.8	20.1	41.7	76.7	37.0
3.5-4.0	12.5	12.7	154.3	100.0	23.3
Seive loss Total wt.	0.7 53.7				

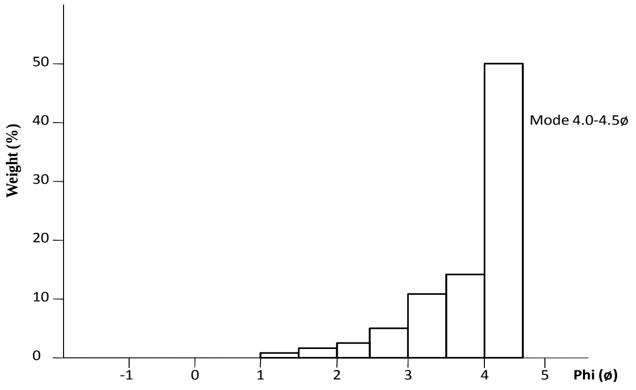


Fig. 8: Histogram plot for white sandstone of upper Mamu.

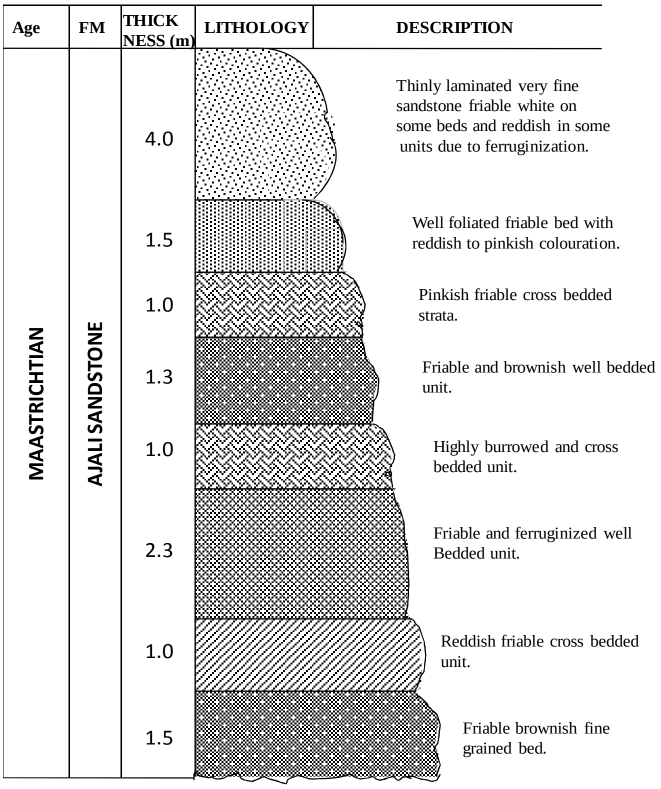


Fig. 9: Lithologic profile of Ajali Sandstone

Paleontology

The ichnofossils such as burrow fills, trails and preserved leaf impressions are recognized (Fig. 11). The characteristic reticulate venation pattern of some the leaf impressions suggests that they are typical dicot plant [30]. Plant fragments are found in the mudstone or claystone interbedded with the sandstone. Bioturbation structures are commonly found as ichnofossils [31]. "Banerjee [32] recognized presence of plant fragments in thinly laminated shale and mudstones in Ajali sandstone at Nkpologu southwest of Nsukka", and these can be correlated with those of the studied area in Nsukka southeast.

Grain-size: Microscopic studies show that the dominant mineral is medium grained quartz crystals with a small amount of matrix and few opaque minerals probably iron oxide [11], [20], [21], [22], [24]. The matrix is made of silt-size quartz and no feldspar is found (Fig. 12). The modal analysis of the framework elements shows; quartz (95%), matrix (10%) and opaque (4%).

Monocrystalline quartz = 95%
Polcrystalline quartz = 5%

The grains are equant to subequant and are predominantly subangular to subrounded (Table 5). Many large polycrystalline quartz grains have been found to break along individual grain boundaries, indicating a textural inversion [33]. They therefore concluded that significant portion of the finer sand and silt fraction could come from fragmentation of large polycrystalline quartz in a dynamic environment.

Table 3: Analysis of cross beds in Ajali Sandstones.

N0.	AZIMUTH OF CROSS BEDS	SIN Θi´	COS Θi	i - Θ	(i - Θ)^2
1	280°	0.9848	0.1736	31.92	1018.88
2	270°	1.0000	0.0000	21.92	480.49
3	295°	0.9063	0.4226	46.92	2201.49
4	330°	0.5000	0.8660	81.92	6710.89
5	275°	0.9962	0.0872	26.92	724.69
6	335°	0.4226	0.9063	86.92	7555.09
7	240°	0.8660	-0.5000	-8.08	65.29
8	272°	0.9994	0.0349	23.92	572.17
9	260°	0.9848	-0.1732	11.92	142.09
10	310°	0.7660	0.6427	61.92	3834.09
11	315°	0.7071	0.7071	66.92	4478.29
12	300°	0.8660	0.5000	51.92	2695.69
13	385°	0.9659	0.2588	36.92	1363.09
14	305°	0.8192	0.5735	56.92	3239.89
15	238°	0.8480	-0.5299	-10.08	101.61
16	245°	0.9063	-0.4226	-3.08	9.49
17	338°	0.3746	0.9272	89.92	8085.61
18	320°	0.6427	0.7660	71.92	5172.49
19	295°	0.9063	0.4226	46.92	2201.49
20	235°	0.8192	-0.5736	-13.08	171.09
21	282°	0.9781	0.2079	33.92	1150.57
22	280°	0.9848	0.1736	31.92	1018.89
23	310°	0.7660	0.6427	61.92	3834.09
24	340°	0.3420	0.9397	91.92	8449.29
25	335°	0.4226	0.9063	86.92	7555.09
∑ Θi = 1		19.77	7.96		72831.8

Table 4: Seive analysis for white sandstone of upper Mamu.

Phi (ø)	Wt. Retained on Seive	Corrected wt.	Cumulative wt.	Cumulative wt. %	Weight (%)
> 2.0 -2.0- 1.5 -1.5- 1.0 -1.0- 0.5 -0.5- 0.0 0.0- 0.5 0.5- 1.0 1.0- 1.5 1.5- 2.0 2.0- 2.5 2.5- 3.0 3.0- 3.5 3.5- 4.0 4.0- 4.5 > 4.5	0.6 0.5 2.2 3.8 6.4 9.8 14.2 8.8 4.7 1.9 1.2 1.7 0.7	0.6 0.5 2.2 3.8 6.5 9.9 14.3 8.9 4.7 1.9 1.2 0.7 0.7	0.6 1.1 3.3 7.1 13.6 23.5 37.7 46.6 51.3 53.2 54.4 55.1 55.8	1.0 2.0 5.9 12.8 24.4 42.1 67.6 83.6 92.0 95.3 97.4 98.7 100.0	1.0 1.0 3.9 6.9 11.6 17.7 25.5 15.9 8.4 3.4 2.1 1.3 1.3
Seive loss Total wt.	0.41 55.4				

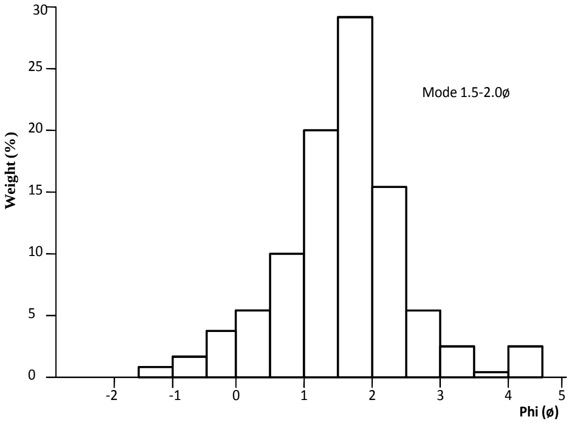


Fig. 10: Histogram plot for Ajali Sandstone

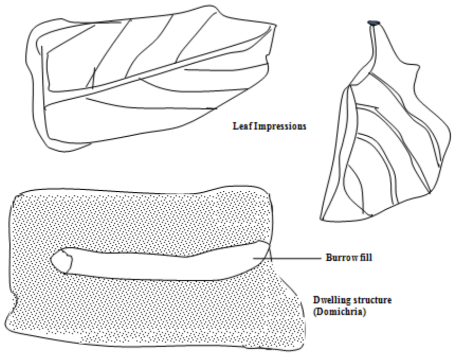


Fig. 11: Ichnofossils in Ajali Sandstone

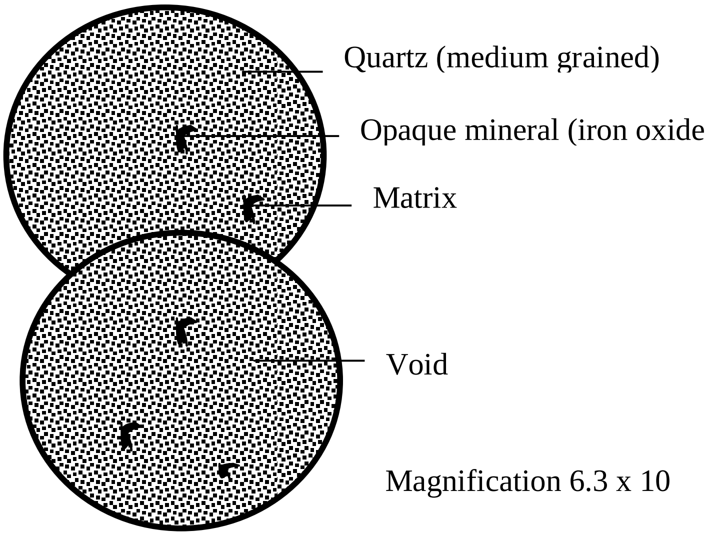


Fig. 12: Thin section view of Ajali Sandstone (medium grained)

Table 5: Thin section textural study of the Ajali Sandstone.

N0.	MINERAL GRAIN	L (mm)	W (mm)	W/L SPHERICITY	ROUNDNESS	EXTICTION	STRUCTURE	GRAIN TO GRAIN ~~CONTACT~~		
								LINE	POINT	CONCAVE-CONVEX
1	Quartz	0.23	0.11	0.48	SR	Straight	M	-	2	-
2	″	0.31	0.12	0.38	SA	″	M	-	3	-
3	″	0.25	0.10	0.40	SR	″	M	-	1	-
4	″	0.23	0.14	0.61	SA	″	M	1	-	-
5	″	0.18	0.10	0.56	SA	″	M	1	-	-
6	″	0.14	0.11	0.79	SR	″	M	-	-	2
7	″	0.23	0.12	0.52	SR	Wavy	P(2)	1	-	-
8	″	0.14	0.10	0.71	SR	Straight			1	-
9	″	0.25	0.10	0.40	SR	″	M	-	1	-
10	″	0.23	0.12	0.52	SA	″	M	1	1	-
11	″	0.25	0.11	0.44	SR	″	M	1	-	1
12	″	0.18	0.09	0.50	A	″	M	-	1	-
13	″	0.25	0.10	0.40	SR	″	M	-	-	1
14	″	0.12	0.10	0.83	SR	″	M	-	2	-
15	″	0.14	0.09	0.64	SR	″	M	-	-	-
16	″	0.20	0.08	0.40	SR	″	M	-	3	-
17	″	0.23	0.14	0.61	SR	″	M	-	-	1
18	″	0.23	0.12	0.52	SA	″	M	-	1	-
19	″	0.10	0.09	0.90	SR	″	M	-	-	-
20	″	0.12	0.10	0.83	SR	Wavy	M	-	-	1
21	″	0.14	0.10	0.71	SR	Straight	P(2)	-	2	-
22	″	0.10	0.09	0.90	SR	″	M	-	1	1
23	″	0.18	0.12	0.67	SR	″	M	1	1	-
24	″	0.35	0.18	0.51	SR	″	M	-	2	-
25	″	0.08	0.04	0.50	SR	″	M	-	-	2
26	″	0.18	0.10	0.56	SR	″	M	2	1	-
17	″	0.10	0.08	0.80	SA	″	M	-	3	-
28	″	0.35	0.10	0.30	SR	″	M	-	2	-
29	″	0.12	0.11	0.92	R	″	M	-	1	-
30	″	0.25	0.20	0.80	SR		M	-	2	-
	∑	5.86	3.26	18.1						
	Mean	0.20	0.11	0.60						

Note: A=Angular; SA=Subangular; SR= Subrounded; R= Rounded; M= Monocrystalline; P(2)=Polycrystalline (with two crystals).

Ajali Sandstone Environment of Deposition

In the studied area Ajali is characterized by presence of fine to medium grained sandstone, small scale cross-beds, leaf impressions, burrow-fills and absence of calcareous and carbonaceous matters. These suggest a continental environment or fluviatile environment. “Reyment [3], [34] suggests that Ajali was deposited in a continental environment”. “Hoque and Ezepue [33] gave a detailed account of petrology of Ajali sandstones and confirmed the earlier views as regards its depositional environment viz continental (fluvio-deltaic)”.

Stratigraphic Correlation

There are six sections across the entire studied area that exhibits characteristic lithologic variations within each lithologic unit. Ajali Sandstone is medium to fine grained and typical cross-bedded. The lower Mamu formation is characterized by subunits sandy shale grey and carbonaceous shales with sandstones mudstones bands and upper Mamu consists of white sandstone. Finally, the Enugu Shale at base is distinguished by three subunits soft dark and bluish carbonaceous shale, grey shale and sandy alternating with siltstones upwards (Fig. 4A). The B profile also shows similar lithologic variations within each of the four lithologic units correlatable with A, C and D profiles.

For more detailed correlation of the lithologic units in the studied area, two more traverse were taken along Ezimo-Agu road passing through Iyi-nzu stream channel which shows an excellent exposure of Mamu formation with coal seams. The other traverse was taken along Opi new road cut at the southern part of the studied area and this has exposures of all the four lithologic units in the area. These four lithologic units are exposed sequentially from Ajali Sandstone on top, upper Mamu white sandstones, lower Mamu, and finally to Enugu shales at the base (Fig. 4E) along Opi new road cut [21].

Structural Styles

Bedding: Bedding and laminae structures are characteristic sedimentary features common to three major lithologic units; Enugu shale, Mamu formation and Ajali sandstones in the studied area. The variation in bedded nature of these sedimentary units is produced by differences in texture, composition, colour and orientation of their original sediments [35].

Graded Bedding: Typical graded beddings are recognized in lower Mamu and white sandstones of upper Mamu along Opi road cut. This is an indication that the transporting current is weak and moves only light particles and these spread out as fine grains [36]. It is also an evidence of the product of sedimentation from suspension in which all sizes are carried and out of which they settle. Genetically, graded bed in each successive increment is similar to the proceeding except that it contains less coarse grains.

In the lower Mamu along Opi road cut, the sequence is as follows; coarse to medium sandstone at the base; fine sandstones very fine sandstones, shale intercalation, and weathered clay at top. This shows fining upward sequence.

Cross Bedding: In the studied area two main types of cross-stratifications are found in Ajali sandstones and lower Mamu member. These are planar tabular and simple tabular cross-beds respectively according to [37] classification scheme.

The Ajali sandstone is cross-bedded on large scale, with the forest laminae making angles of 20o to 25o with major bedding planes (Fig. 13a). The bounding surfaces of planar tabular cross beds are planar surface of erosion or non-deposition. Simple tabular cross bed is recognized along the channel of Ugene streams in lower Mamu formation. The tabular cross beds range in thickness from 6cm to 40cm. In this simple tabular cross-bed the bounding surface is non-erosional surface. Each trough set consists of an elongate erosional scours infilled with curve laminae (Fig. 13b). The rose diagram plot of cross-beds indicates westerly to northwest direction for paleocurrent (Fig. 14b).

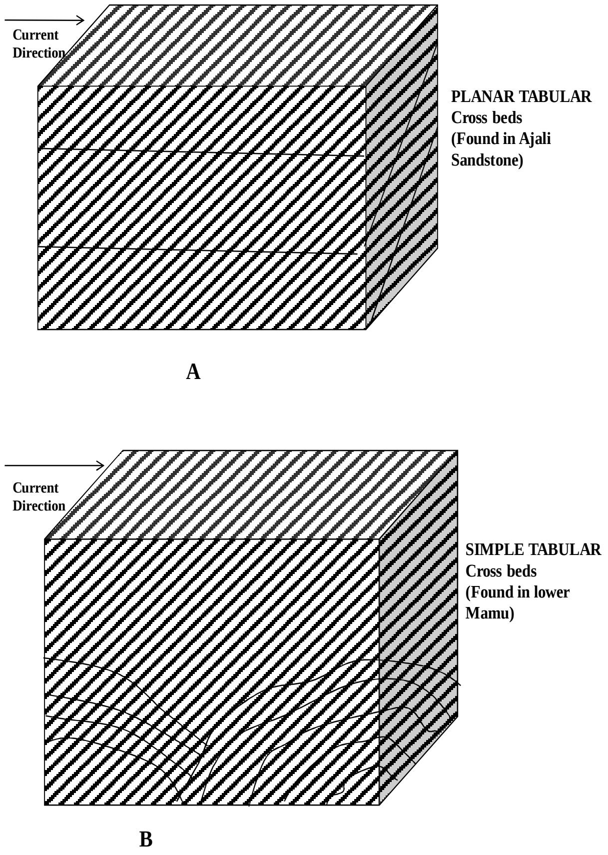


Fig. 13: Block diagramtic representation of Planar (A) and Simple (B) tabular cross beds (modified from [37])

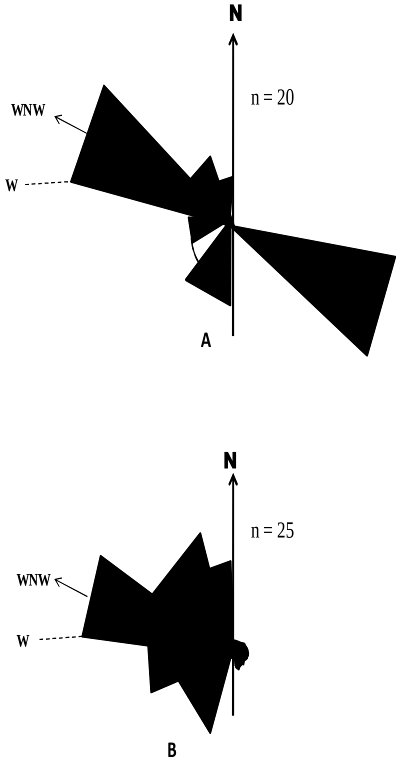


Fig. 14: Rose diagram for Joints (A) and Cross beds (B) in the studied area.Note: n = Number of observations

Burrowing: The Ajali sandstones at Ugwu-Ikwube and sandy grey shales of Mamu formation are commonly burrowed. The burrow-fills or bioturbation structures such as track, trails and burrows are evidences of the activities of organisms and are known as ichnofossils. Bioturbation structures are numerous in the Ajali Sandstones at Ugwu-Ikwube. The burrow-fills represent dwelling structures of the organisms and are known as Domichnia [38]. The burrow-fills are tunnel and shaft like. They range in size from 1cm to 9cm long and the diameters are commonly uniform. Most of the burrow fills are horizontal and some are oblique. The burrowing habit of animals living in a sandy environment may be as a result of bottom scour [19]. Abundant leaf impressions are recognized in Ajali sandstones and sandy grey shales of Mamu Formation.

Concretions: Abundant concretional structures are contained in both the sediments of the Enugu shales and Mamu Formation. They are of many shapes and sizes and vary from elongate, radial to almost spherical shapes. The sizes range from 3cm to 10cm in diameter. Most of the concretions have no well defined nucleus, but some have small plant fragments which form centres about which the concretion is built.

“Pettijohn [19] recognized that most of the concretional structures are formed by segregations of minor constituent of rock containing the concretion most especially the iron sulphide of the black shale and other minor elements in rock”.

Joints: With the exception of Ajali Sandstone, the Enugu shales and the Mamu Formation are well jointed. Most of the joints are vertical and parallel to the direction of dip. The joints in the studied area can be described as dip joints [39]. They commonly trend in W-WNW (Fig. 14A). The mean strike direction of these joints is 254.4o azimuth (Table 3). They are tight joints and no form of mineralization is found on their walls. Most streams in the studied area are joint controlled since they almost trend in the same direction as those joints. For instance most of the streams flow W-E direction whereas the main strike direction of the joints is SW-NE.

Ripple Folds: Ripple folds are common to the bedding and lamination structures in Mamu and Ajali sandstone formations. Abundant of ripple folds are recognized in lower Mamu along Opi road cut. The mean strike and plunge of ripples in the studied area are 65o azimuth and 7o respectively. The steronet plot of the ripple folds indicates that the paleocurrent directions in the area are NE and SW which are perpendicular to the general trend of strikes (Fig. 15, Table 6). This implies that there were two sources of sediments into the studied area.

Landslides: Landsliding is a common structural feature in Ajali Sandstone in the studied area. The Ajali Sandstone is undercut by erosion and stream and this result in shearing of rock masses and sliding. Landsliding forms deep canyon gullies along the slope of Enugu escarpment and exposes thin shale bands.

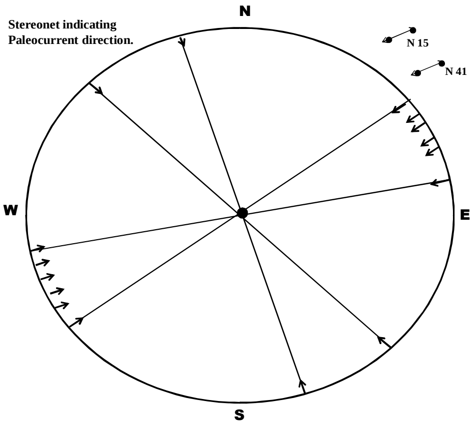


Fig. 15: Stereonet (Ripples)

The Drainage System

The studied area has a drainage system which is structural controlled by the trend of joints. The joints controlled streams appear to flow in a general pattern. Most of the major streams flow from Ajali eastwards at the foot of Enugu escarpment and have a variety of valley form corresponding to the nature of rocks on which they are flowing. Three main types of valley forms are distinguished; a) V-shaped gullies of Ajali Sandstone, b) Waterfalls of the harder rocks of the escarpment and c) Broad sandy valley of the plains.

Table 6: Summary of joints (Rose diagram) in the studied area

Joints	Strike	Dip
1	210	Vertical
2	180	″
3	270	″
4	180	″
5	320	″
6	275	″
7	225	″
8	190	″
9	250	″
10	290	″
11	270	″
12	355	″
13	295	″
14	277	″
15	280	″
16	285	″
17	260	″
18	320	″
19	340	″
20	300	″

Interval	Frequency	Radius equivalent (cm)
180-209	3	1.5
210-239	2	1
240-269	2	1
270-299	8	4
300-329	3	1.5
330-359	2	1
	20	10

The contacts between Ajali Sandstone and Mamu Formation at foot of Enugu escarpment form the sources of major streams such as Igbogbo, Iyi-coal at Eha-ndiagu, Amanyi at Orba, Iyi-nzu at Ezimo and Uhere at Opi and form deep valley which expose the thin laminated shale below. The contacts show that Ajali Sandstones form good aquifers in the studied area.

Petroleum System and Petroleum Potential in the Anambra Basin

Generally, the most viable petroleum system in the Anambra Basin is perhaps the Upper Cretaceous system as observed by [40]. This system may further be subdivided into the pre-Santonian and post-Santonian subsystems. The pre-Santonian subsystem consists of the Ezeaku and Awgu Formations as potential source rocks, the sandy members within the Awgu Formation (e.g. the Coniacian Agbani Sandstone Member) as potential reservoirs, and the basal part of the Nkporo/Enugu Formations as regional seal [41]. The post-Santonian subsystem should consist of the shale of the Nkporo/Enugu Formations as major potential source rocks (including the coals and coaly shale of the Mamu and Nsukka Formations), the potential reservoirs consist of sandstones of the Nkporo/Enugu Formations (e.g. the Campanian Oweli and Otobi Sandstone Member), the sandy horizons in the Mamu Formation, the Ajali Sandstone, the sandy horizons of the Nsukka Formation and perhaps the sandstones of the Imo Formation (e.g. the Palaeocene Ebenebe Sandstone Member). Potential regional sealing lithologies could be the shales of the aforementioned potential source rocks and the shale of the Imo Formation within the context of their stratigraphic position vis-à-vis the stratigraphic location of the potential reservoirs [35], [42].

Rock-Eval pyrolysis data of potential source rocks of the Anambra Basin is shown in [43]. TOC values range from 0.33-7.28wt% (ave. 2.52wt %) in the pre-Santonian Ezeaku and Awgu Formations with an exceptionally high values of 3-10wt% in the Lokpanta Member (Fig. 2) of the Ezeaku Formation. This indicates that the pre-Santonian formations have adequate organic matter quantity for hydrocarbon generation. The HI ranges from 38-587mgHC/gTOC (ave. 177mgHC/gTOC) for the Ezeaku and Awgu Formations, except again the Lokpanta Member (200-600mgHC/gTOC, [43] with values not less than 200mgHC/gTOC. In the 'mainstream' Ezeaku and Awgu Formations most of the samples have values? 50mgHC/gTOC but <150mg/gTOC [43]. HI values in the 'mainstream' Ezeaku and Awgu Formations indicate the predominance of type III (gas-prone) organic matter while the shale of the Lokpanta Member are typeI/II (oil and gas-prone). Tmax values range from 426-437oC (ave. 431oC) for the 'mainstream' Ezeaku and Awgu Formations and 450-600oC for the Lokpanta Member [43]. Although Tmax values of the 'mainstream' Ezeaku and Awgu Formations suggest immaturity-marginal maturity, [44] observed that the two formations were exposed to burial temperatures in excess of 150oC before the advent of the mid-Santonian tectonic event and perhaps were matured and had generated hydrocarbons before the event. Rock-Eval pyrolysis data of the potential source rocks of the post-Santonian formations indicates TOCs of 0.31-3.51wt% (ave. 1.86wt%), 0.82-6.10wt% (ave. 2.78wt%), 30.80-60.80wt% (ave. 40.03wt%) and 0.50-0.82wt% (ave. 0.80wt%) for the Nkporo/Enugu Formation, coaly shale of the Mamu Formation, coals of the Mamu Formation and Nsukka Formation respectively. These indicate adequate organic matter quantity for hydrocarbon generation. The HI is in the range of 7-327mgHC/gTOC (ave. 68mgHC/gTOC), 245-306mgHC/gTOC (ave. 130mgHC/gTOC), 266-327mgHC/gTOC (ave. 297mgHC/gTOC) and 31-63mgHC/gTOC respectively. Organic petrographic data from coals of the Mamu and Nsukka Fromations indicates the predominance of vitrinite/huminite [45]. All these parameters indicate predominantly type III with perhaps limited occurrence of type II organic matter. This indicates to the capability to generate mainly gas on maturity. This deduction was earlier observed by [40], [46], [47], [48]. Generally, the potential source rocks of the post-Santonian petroleum subsystem are immature (mostly less than the minimum threshold of the 435oC) except perhaps some parts of the Nkporo/Enugu Formations which may be marginally mature.

As earlier mentioned, the potential reservoir rocks in the Anambra Basin are the associated sandstone facies of the predominantly shale lithology of the basin (Fig. 2). According to [40] sedimentation in the Anambra Basin was dominantly terrigenious resulting in up to 3000m thick shale (60%), sand (40%) and limestone (<1%).

"Onuoha [49] identified three hydrostratigraphic units in the

Anambra Basin that includes;

I. Quaternary deposits and sandy horizons of the Ameki Formation,
II. The Ajali Sandstone, the sandy horizon of the overlying Nsukka Formation, and the upper part of the underlying Mamu Formation,
III. Sandy beds in the Awgu, Nkporo and of the lower Mamu Formations".

The first hydrostratigraphic unit is very shallow (approximately not more than 500m deep to form viable reservoir."Ladipo et al. [12], [40] inferred that the Mamu and Nsukka Formations are probably delta front sand bars". Ajali Sandstone on the other hand was attributed to fluvial deposition [50] characterized by large channels containing lithic fill of fining upward pebbly sandstones [40]. It is also related to the development of shallow marine subtidal sand bars [12], [51]. These potential reservoir sands are mostly laterally extensive and may reach local thickness of up to 5051ft (> 1000m) where stacked.

IV. CONCLUSIONS

The studied area which is within Anambra Basin is made up of three major formations; the Enugu Shale, the Mamu Formation and the Ajali Sandstone. These formations were deposited during the second sedimentary cycle and their ages range from upper Campano-Maastrichtian.

The Campano-Maastrichtian Enugu shales are made up of three subunits; soft dark bluish carbonaceous shale, grey shale and sandy shale. The Mamu Formation which overlies the Enugu shale is made up of two members; the lower and the upper Mamu. The lower Mamu comprises of three subunits; the carbonaceous shale, grey shale and sandy shale. The upper Mamu is made of one unit which is fine grained friable white sandstones.

The Ajali Sandstone the youngest of three formations overlies the Mamu Formation in the studied area. It consists of poorly consolidated, friable medium grained sandstones and pinkish to reddish colour and some ironstained with thin white bands of mudstones and shale at various intervals. It is typically cross-bedded on large scale, highly burrowed and contains plant impressions as ichnofossils.

The studied area within the Anambra Basin seems to have high economic potentiality for hydrocarbon accumulation. A more detailed exploration should be done in the studied area and even the entire Anambra Basin in order to know about the extent of hydrocarbon reserves in this region.

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