Original scientific paper

Received: October 19, 2012
Accepted: May 27, 2013

Sedimentological characteristics, provenance and hydrocarbon potential of Post Santonian sediments in Anambra Basin, Southeastern Nigeria

Sedimentološke značilnosti, izvor in potencial ogljikovodikov postsantonijskih sedimentov v kadunji Anambra v jugovzhodni Nigeriji

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Abstract

Field studies of outcrop samples from part of Anambra basin, southeastern Nigeria, were investigated to unravel the lithofacies distribution, provenance, palaeotectonic history as well as aspects of hydrocarbon potential of the basin. The sandstone facies of the Nkporo, Owelli, Mamu and Ajali Formations are cross bedded, medium to coarse grained, poorly sorted to moderately well sorted, negatively skewed and leptokurtic to platykurtic. Textural plots and multivariate parameters indicate fluvial to shallow marine environment. Paleocurrents signify southwest direction for the Nkporo and Ajali Formations while the Owelli Formation points to a northwest direction. The sandstones classify as quartz arenite with heavy mineral assemblages that revealed the presence of zircon, rutile, tourmaline, staurolite, sillimanite, kyanite, garnet and apatite; having ZTR index of 63 %. These typify products of weathering of basement rocks under humid climatic setting with long transportation and/or recycling history. Organic matter quantity of the shales ranges from mass fractions 0.89 % to 3.98 % TOC and Rock-eval parameters indicate immature, poor to fair hydrocarbon potential. Cross plots of rock eval parameters revealed gas proned terrestrially derived Types III and IV kerogen. It can be deduced that the sandstones were sourced from the Adamawa–Abakaliki folded belt and part of Oban Massif while the shales have prospect to generate gas at appropriate maturation, especially from the Nkporo Shale.

Key words: sedimentology, provenace, palaeoenvironment, hydrocarbon potential, Anambra Basin

Izvleček

Vzorce izdankov iz dela kadunje Anambra v jugovzhodni Nigeriji so preiskali z namenom ugotoviti porazdelitev litofaciesov, izvor, paleotektonsko zgodovino in značilnosti naftnega potenciala v kadunji. Za faciese peščenjakov formacij Nkporo, Owelli, Mamu in Ajali so značilne navzkrižna plastovitost, srednja do debela zrnavost, slaba do srednja sortiranost, negativna asimetričnost in lepto- do platikurtičnost. Teksturni diagrami in multivariatni parametri nakazujejo rečno do plitvomorsko okolje. Paleotokovi imajo jugozahodno usmerjenost v formacijah Nkporo in Ajali ter severozahodno v formaciji Owelli. Peščenjaki spadajo h kremenovem arenitu s težkomineralnimi združbami, ki vsebujejo cirkon, rutil, turmalin, stavrolit, sillimanit, kianit, granat in apatit z ZTR-indeksom 63 %. Predstavljajo produkte preperevanja kamnin podlage v vlažnem podnebju z dolgim transportom in/ali recikliranjem. Masni delež organske snovi v glinavcih se giblje med 0,89 % in 3,98 %. Vrednosti TOC in rock-eval nakazujejo nezrel, nizek do srednji potencial ogljikovodikov. Navzkrižni diagrami rock-eval-parametrov določajo plinsko usmerjeni kerogen terestričnega izvora tipov III in IV. Sklepajo, da so bili peščenjaki napajani iz nagubanega pasu Adamawa–Abakaliki in delno masiva Oban. Glinavci, zlasti glinavec Nkoporo, utegnejo ob primerni dozorelosti proizvajati plin.

Ključne besede: sedimentologija, izvor, paleookolje, potencial ogljikovodikov, kadunja Anambra

Introduction

The origin of Anambra Basin is related to the evolution of the Benue Trough, which is also associated with the separation of the African plate from South American plate in the Mesozoic (Tijani et al., 2010). As reported by Akande & Erdtmann, (1998) it is logical to include the Anambra Basin in the Benue Trough, being a related structure that developed after the compressional stage. The basin covers an area of approximately 40 000 km^2 (Nwajide & Reijers, 1996) with approximate sediment thickness of 5 000 m (Uma & Onuoha, 1997). The Anambra basin is characterized by enormous lithogenic heterogeneity in both lateral and vertical extensions derived from a range of paleoenvironmental settings, ranging from
Campanian to Recent (Akaegbobi, 2005).

The initial interest in search for oil and gas within the Lower Benue Trough (including the Anambra Basin) of Nigeria, aroused by the presence of favourable stratigraphic setting of interbeded shales and sandstones with occasional limestones (Agagu et al., 1985). The exploration for coal and petroleum in the Anambra Basin culminated into commercial production of coal in 1916 while oil exploration was abandoned as the efforts ended in a number of non-commercial discoveries. The search for commercial hydrocarbons in the Anambra Basin in Nigeria has been a concern, especially to oil companies and research groups, more so as oil is found in the nearby Niger Delta. In addition, sedimentological characteristics of different litho-units have not been fully discussed on a regional scale.

This study therefore examines sedimentological charateristics, provenane, palaeoclimatic and palaeodepositional conditions as well as aspects of hydrocarbon potential of the sediments of Anambra basin from outcrop studies. Such studies would be useful to researchers and explorationists.

Location of study area and stratigraphy of Anambra basin

The study area lies within latitudes 5°55’ N to 6°30’ N and longitudes 7°20’ E to 7°30’ E and belongs to the Anambra Basin (Figure 1). The locations of sampling are shown as 1 to 7 in Figure 1.

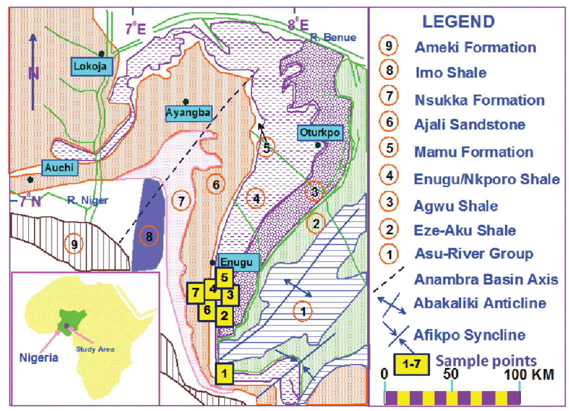


Figure 1: *Regional stratigraphy of southeastern Nigeria with the sample points (after Tijani et al., 2010).*

The oldest sediment in the southern Benue Trough is the Asu River Group (Nwajide, 1990). It consists of about 3 000 m of micaceous sandstones, mudstones, sandy shales, siltstone and limestone lenses. The succession was uplifted and became the topographic provenance (Abakaliki Anticlinorium), which supplied the bulk of the Anambra Basin fill (Hoque, 1977). According to Reyment (1965) and Burke et al. (1972), the sediments are of Albian to Turonian age and were deposited under shallow marine or near shore conditions. The Asu River Group is overlain by the Eze-Aku Formation, which is of Turonian age (Reyment, 1965; Nwajide, 1990). It comprises hard grey-black shales and siltstones with frequent facies changes to sandstones or sandy shales (Petters, 1978; Kogbe, 1989). The Awgu Formation conformably overlies the Eze-Aku Formation. It consists of grey to black well bedded, fissile shales, with thin interbeds of shelly limestone and fine to medium grained/moderately sorted sandstone. Based on the foraminiferal content, Agagu et al. (1985) assigned a Turonian-Santonian age and a shelf depositional environment to the Awgu Formation.

In the Santonian, there was a major tectonic event in which the Albian-Coniacian sediments were deformed, folded, faulted and uplifted (Benkhelil, 1989). This marked the period of sediments deposition within the Anambra Basin (Nwajide, 1990; Tijani et al., 2010). The oldest sediments within the basin is the Nkporo Group. It was deposited into the basin in Late Campanian and comprised Nkporo Shale, Owelli Sandstone and Enugu Shale (Reyment, 1965; Obi et al., 2001). The Nkporo Group is overlain by parallic succession made up of siltstone, shale, coal seam and sandstone units of Mamu Formation deposited in the Early Maastrichtian (Kogbe, 1989). On the basis of organic geochemical and biomarkers parameters, Nton & Awarun (2011), described the shale and coal units of the Mamu Formation as moderate to rich oil/gas proned, immature source rocks of terrestrial precursor.

The Mamu Formation is successively overlain by cross-bedded, tidal channel/fluvial deposits that constitute the Maastrichtian Ajali Sandstone (Ladipo, 1986). The Ajali Sandstone, formerly known as the false-bedded sandstone (Simpson, 1954) consists of friable, medium to coarse grained, poorly sorted, cross bedded sandstones with thin beds of whitish claystones as well as numerous bands of variegated carbonaceous shale (Reyment, 1965 and Agagu et al., 1985). Ajali Sandstone is succeeded by the Nsukka Formation (upper coal measure) which is of Late Maastrichtian age (Obi et al. 2003). It consists of carbonaceous mud rocks, sandstones, shales and coal seams (Nwajide, 1990; Obi et al, 2003).The Imo Shale (Paleocene) overlies the Nsukka Formation and comprises clayey shale with occasional ironstone and thin sandstone in which carbonaceous plant remains may occur (Kogbe, 1989).The Imo Shale is later succeeded by the Ameki Group (Reyment, 1965; Nwajide, 1990).

Field sampling and analytical methods

Field exercise was carried out along road cuts within parts of the Anambra Basin (Figure 1). Altogether, seven (7) outcrop locations were encountered. At each location, the outcrop was described, logged, and strike and dips of directional properties were taken. The lithologic profile at each location was sketched and the GPS reading taken as reference. Attempts were made at getting fresh samples which were made up of sandstones, shales and coals. Each sample was described and taken in a well labeled sample bag. Brief descriptions of the different outcrop locations are given below:

Location 1 (Leru Village)

This is a road cut exposure at Leru village representing Nkporo Formation. It is about 54 m thick (Figure 2) and has a lateral extent of about 1.5 km. Based on the different lithologies observed, the formation can be differentiated into shale facies, sandstone facies and sandy shale facies. The basal part of the outcrop starts with a dark shale resting unconformably on a doleritic boulder (Figure 2). It has a vertical thickness of about 7 m and contains bivalves, gypsum and micrite. The dipping direction is 296° Az, trending in 038° N/218° S direction and with a dip of 6°. This is overlain by a thin bed of ferruginised fine brown sandstone of about 5 cm with groove casts. This is later succeeded by a black shale of about 0.8 m containing micrite and gypsum nodules, joints and rootlets. The trending of the bed is 40° N/220° S, dipping along 300° N with dip amount of 7°. It progresses into a thin ferruginised brown shale of about 5 cm, containing bivalves and groove structures which is succeeded by grey shale of about 1 m, having traces of bivalves and gypsum nodules. The section passes into an indurated mudstone of about 4 cm, trending in 22° N/202° S direction; it has a dip amount of about 6°. It is overlain by a grey shale of 2 m thick, interbedded with mudstone and ferruginised at the upper part. The trend of the bed is 22° N/202° S; it has a dipping direction of about 226° W and dip amount of about 5°. Next in succession is a grey shale with an estimated thickness of about 10 m. The shale is fissile and contains bivalves.

Overlying the lower shale facies is a sandstone facies with graded, parallel laminated, poorly sorted, medium to coarse, friable sandstone bed of about 20 m thick (Figure 2). It dips 270° W, trends towards 12° N/192° S and with dip amount of 10°. It continues into a parallel laminated, poorly sorted, friable medium to fine

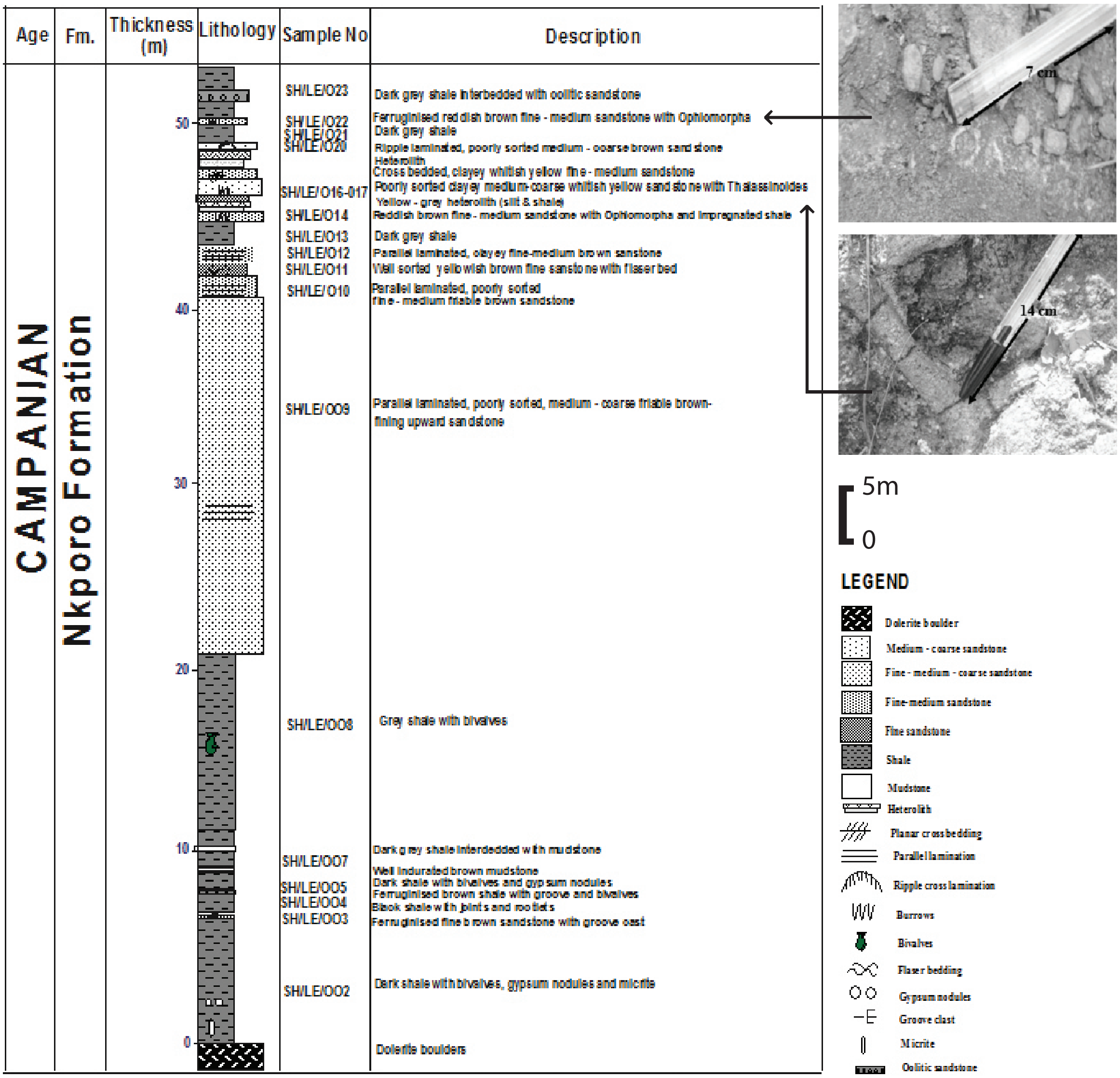


Figure 2: *Lithologic section of Nkporo Formation exposed at Enugu-Port Harcourt express way in Leru Village. Co-ordinate: 5°55′ N and 7°28′ E.*

grained brownish sandstone. It is 1.3 m thick, dips 282° W, trends along 30° N/210° S and with dip amount of 8°. Overlying this, is a well sorted friable, yellowish brown fine sandstone characterised with flaser bed and succeeded by a well sorted, friable, clayey, fine to medium grained brown sandstone.

The uppermost unit consists of sandy shale facies, made up of sequences of shale, sandstone and heterolith. A grey shale with a thickness of about 1.5 m marks the basal portion of this facies. It passes into ferruginised, reddish brown, fine to medium grained sandstone typified by presence of Ophiomorpha (Figure 2) and impregnated shale. The facies continues with a heterolith of 0.7 m thick which is overlain by a friable, clayey, greyish yellow, fine grained sandstone, 0.3 m thick, and succeeded by a poorly sorted clayey, medium to coarse grained whitish yellow sandstone which is 1 m thick, containing Thalassinoides (Figure 2). The section grades into a bed of 0.4 m thickness that is cross bedded, whitish yellow medium grained sandstone. It is overlain by a heterolith of 1 m thickness and passes into a ripple laminated medium to coarse grained brown sandstone of 0.2 m thick with Ophimorpha. This is overlain by dark grey shale which is 1 m thick, trending 40° N/220° S, dipping 308° W and having dip amount of about 7°. The dark grey shale is overlain by 0.2 m thick ferruginised reddish brown fine to medium grained sandstone with Ophiomorpha burrows. The section terminates with dark grey shale which is 3 m thick, interbedded with oolitic sandstone of 0.1 m thickness.

Location 2

This is an exposure of Owelli Formation, encountered south of Enugu along Enugu-Port Harcourt road (Figures 1 and 3). It consists of shale, sand, coal and mudstone beds with a total thickness of about 21 m (Figure 3) and lateral extent of about 700 m. The sequence begins with a grey to brown weathered shale which is 2 m thick interbedded with thin mudstone. It is overlain by 1 m thick, grey–brown ferruginised shale which is succeeded by 2 m thick, poorly sorted, clayey, fine to medium grained brown sandstone with gypsum nodules. The sequence is overlain by 1.7 m dark grey shale, trending 46° N/226° S, dipping 314° W and dip amount of about 8°. It is succeeded by 1.2 m thick dark grey shale trending 44° N/224° S, dipping 3120 W and dip amount of about 7°. Overlying this, is a bed of about 1.1 m of laminated brown mudstone, overlain by 3 cm black coal bed showing considerable degree of partings. This is succeeded by a brown mudstone of about 1.5 m. The section continues with about 0.6 m thick parallel laminated fine to medium grained greyish white sandstone. The sequence is overlain by 0.7 m thick cross bedded yellowish white, poorly sorted, clayey, fine to medium sandstone. It continues into a poorly sorted, clayey, fine to medium grained whitish sandstone which is 0.4 m thick and characterized by herringbone structure (Figure 3). It trends 60° N/240° S, dips 150° E and has a dip amount of about 10°. Successively overlying this, is a parallel laminated, ferruginised, reddish white, fine to medium sandstone about 1 m thickness and passing into a cross bedded, ferruginised, coarsening upward, fine to medium grained white sandstone of about 0.7 m with Ophiomorpha burrows. It is succeeded by poorly sorted, medium to coarse grained yellowish sandstone of about 2 m thick, characterised by *Ophiomorpha* burrows, which is overlain by a dark brown sandstone of about 1 m thick containining vertical burrows of the *Skolithos* ichnogenera (Figure 3). The section is capped by an indurated brown mudstone of about 4 m thick.

Location 3

This location was encountered along the Enugu-Onitsha expressway at Agu Abor. It is a road cut exposure of Enugu Shale with a vertical thickness of about 16.5 m (Figure 4) and lateral extent of about 800 m. The section begins at base with dark grey weathered shale which is 3 m thick, with an extra-formational clast (Figure 4). It is overlain by dark grey shale of about 4.1 m thickness and continues into a parallel laminated siltstone which is about 0.1 m thick. The siltstone is succeeded by dark grey shale of about 2.5 m, bearing extra-formational clast. It passes into a heterolith and transits into dark grey shale of 1.2 m. The top of the section terminates with a dark grey shale of 4 m thickness, which is interbedded with ironstone of about 2.5 cm thickness.

Location 4

This location, encountered at Onyeama Mine, along the Enugu-Onitsha Expressway, is the type section of Mamu Formation. With a total thickness of about 41 m, it consists of a sequence of siltstone, sandstone, coal, mudstone and shale (Figure 5). The sequence begins at the base with yellowish brown, fairly indurated siltstone, 1.5 m thick, and overlain by dark coal beds with high degree of partings which show increasing hardness in an upward direction. The coal beds have 20° N/200° S strike, dip direction of 120° S and dip amount of 4°. The sequence is overlain by 25 m thick yellowish grey mudstone bearing bivalves. It is succeeded by 3 m thick well indurated grey siltstone and grade into well laminated, reddish brown fine sandstone of 2 m thick which is overlain by a yellow siltstone of 2 m thick. The sequence is successively overlain by reddish white, clayey, fine sandstone, then passes into a parallel laminated yellow fine sandstone which is 7.8 m thickness. This is overlain by parallel laminated grey siltstone about 1 m thick and the section is overlain by about 2 m thickness of overburden.

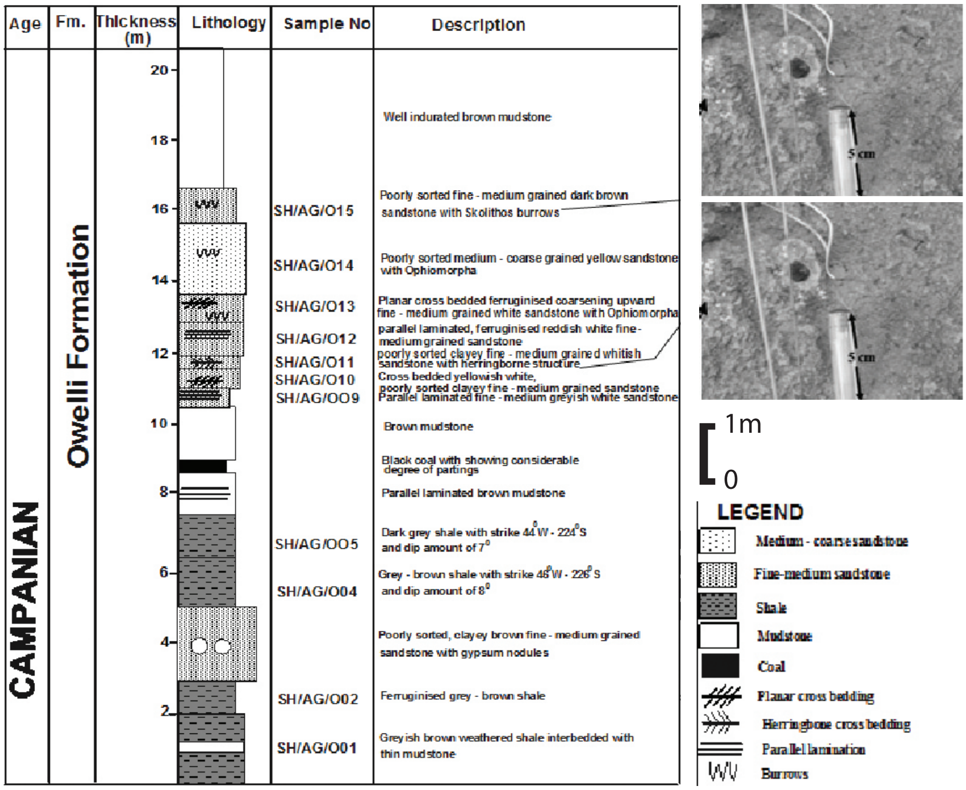


Figure 3: *Lithologic section of Owelli Formation exposed at 30 km south of Enugu along Enugu-Port Harcourt expressway, Agbogugu junction. Co-ordinate: 6°16′ N and 7°28′ E.*

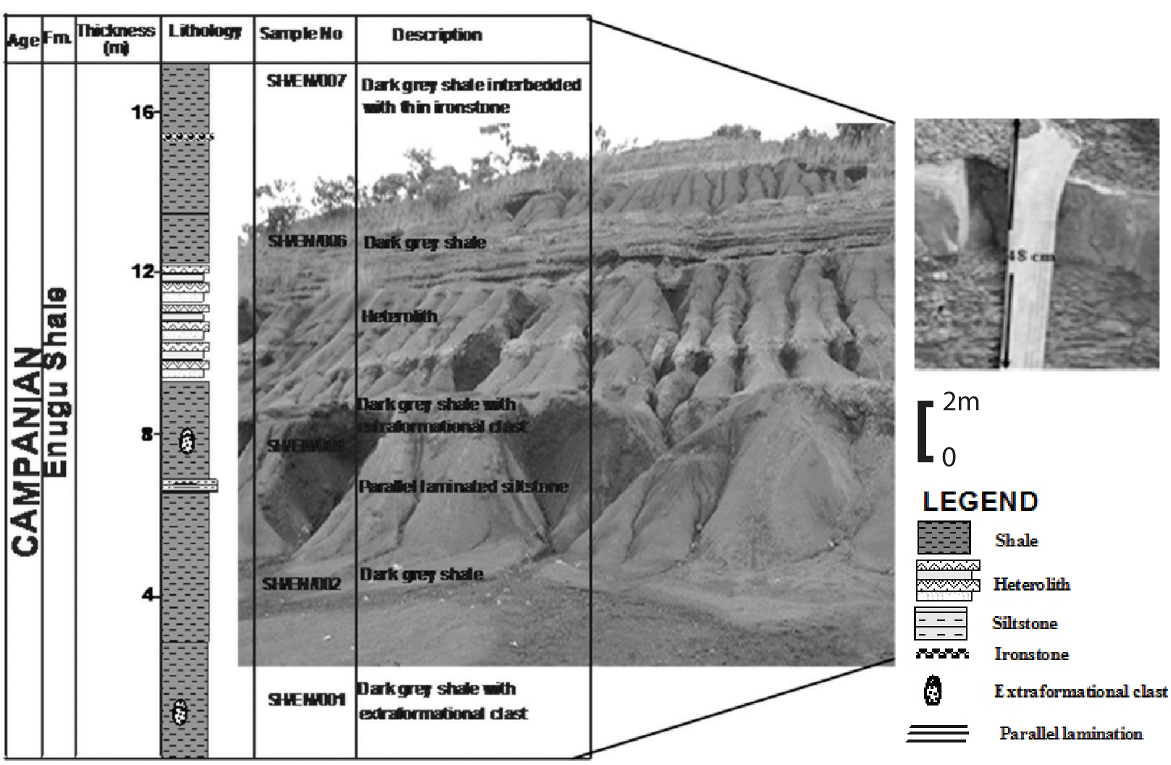


Figure 4: *Lithologic section of Enugu Shale exposed at Agu-Abor near Onitsha road flyover at Enugu. Co-ordinate: 6°26′ N and 7°29′ E.*

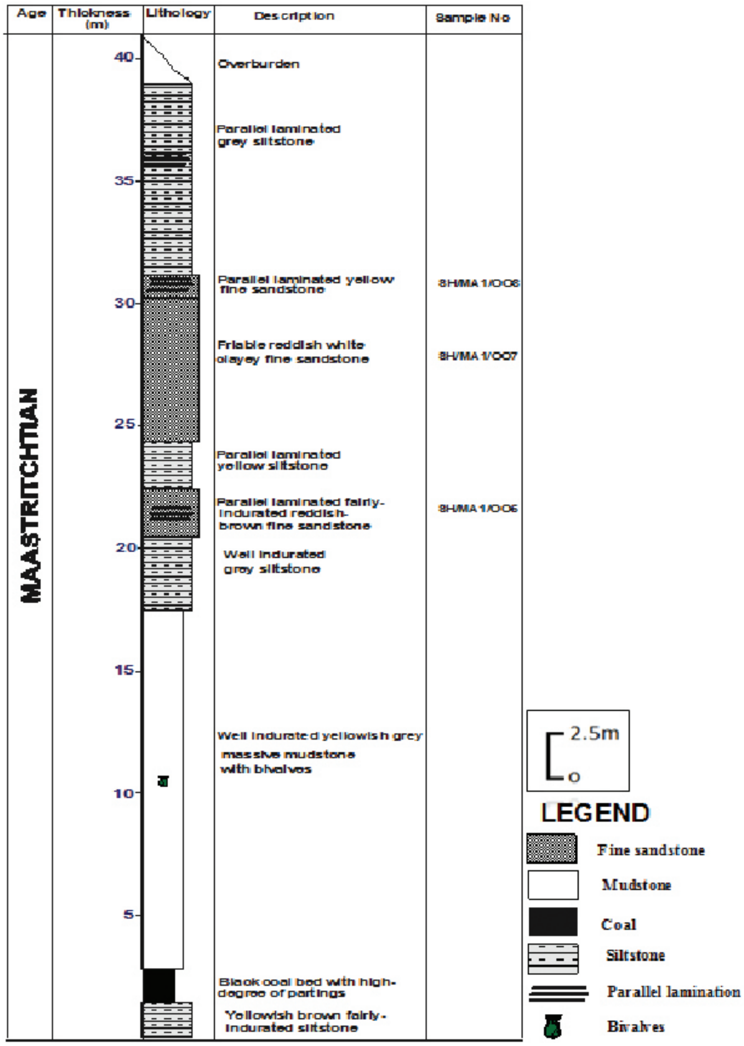


Figure 5: *Lithologic section of Mamu Formation exposed at Onyeama mine, 1.2 km away from NNPC Mega Petrol station at Agu-Abor. Co-ordinate: 6°25′ N and 7°27′ E.*

Location 5

This is a section of Mamu Formation exposed at Proda, half a kilometer away from the NNPC Mega Petrol Station at Agu-Abor, along Enugu-Onitsha expressway in Enugu. It has a vertical thickness of about 20 m (Figure 6) and a lateral extent of about over 500 m. It is made up of a sequence of siltstone, shale and sandstone. The section begins with parallel laminated grey siltstone of about 6.5 m thickness that is overlain by parallel laminated grayish to yellowish siltstone which is about 2.5 m thick. This is successively overlain by 1.5 m thick dark grey shale and then by 0.5 m thick parallel laminated fine grained sandstone. Overlying this sequence is a 5 m thick parallel laminated brownish yellow siltstone which is overlain by massive grayish yellow siltstone about 2 m thickness and then capped by a heterolith of silt and sandstone of 2.5 m thickness.

Location 6

This location shows a vertical thickness of 13 m of Ajali Sandstone (Figure 7) at Ngwo with a lateral extent of about 600 m. The basal bed is made up of poorly sorted, loose, clayey reddish fine grained sandstone which is succeeded by poorly sorted, loose, clayey, cross bedded, white fine grained sandstone. The overall sequence is capped by white colored, poorly sorted, loose, coarse grained sandstone, consisting of herringbone cross bedding and reactivation surface.

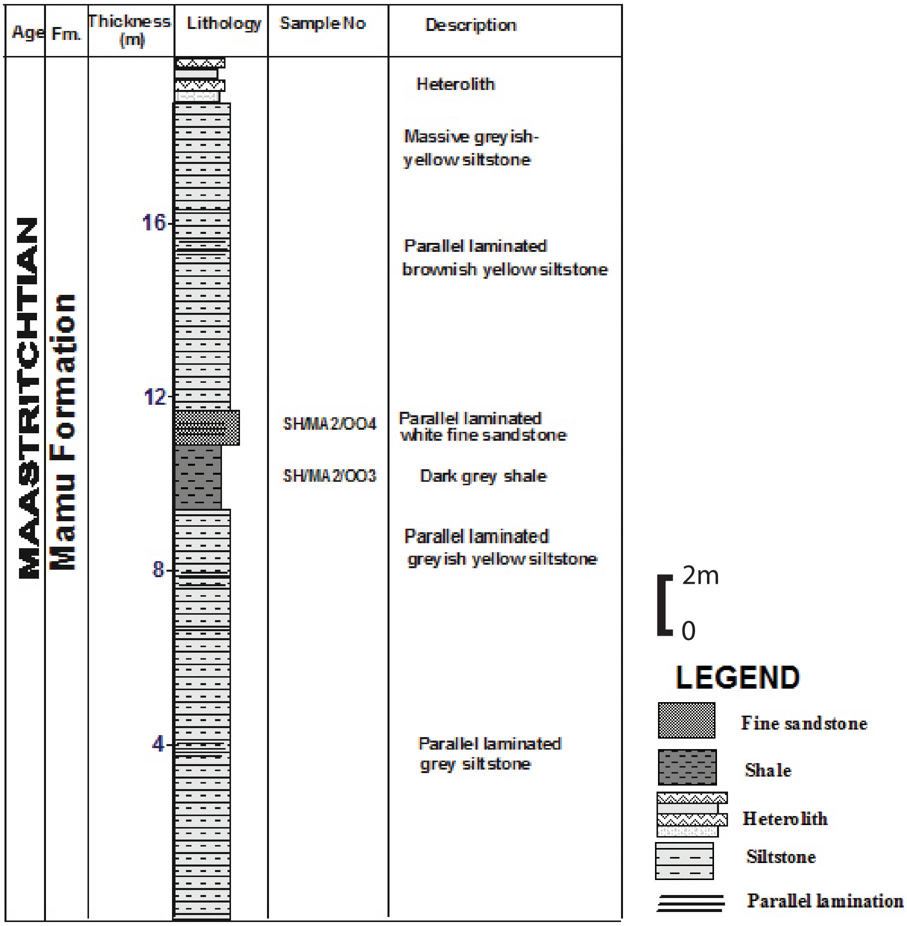


Figure 6: *Lithologic section of Mamu Formation exposed at Proda, 465 m away from NNPC Mega Petrol station at Agu-Abor. Co-ordinate: 6°25′ N and 7°28′ E.*

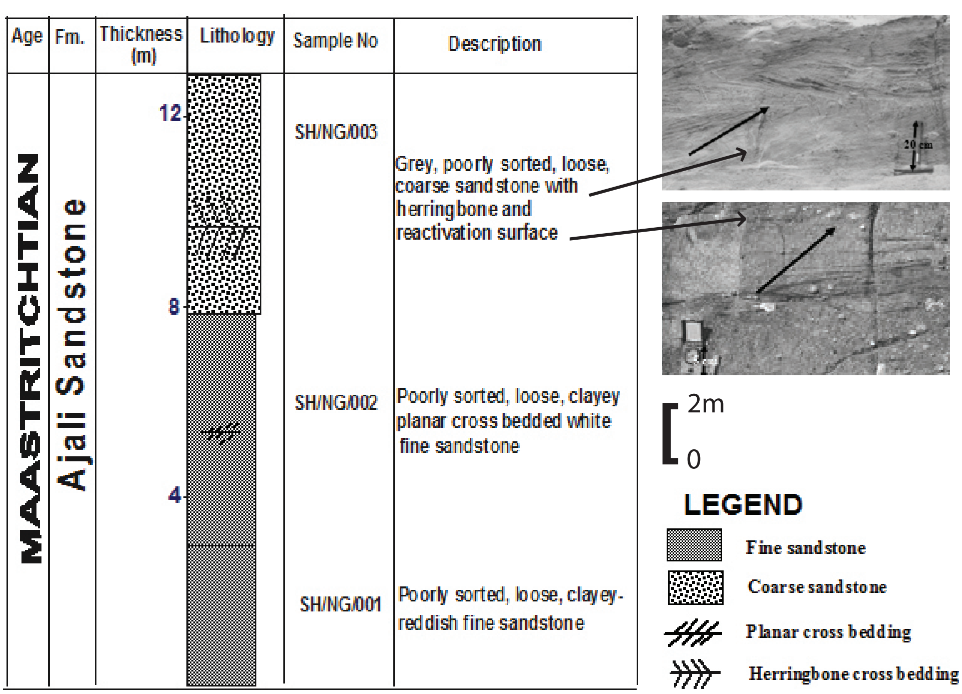


Figure 7: *Lithologic section of Ajali Sandstone exposed at Ngwo, Enugu. Co-ordinate: 6°22′ N and 7°27′ E.*

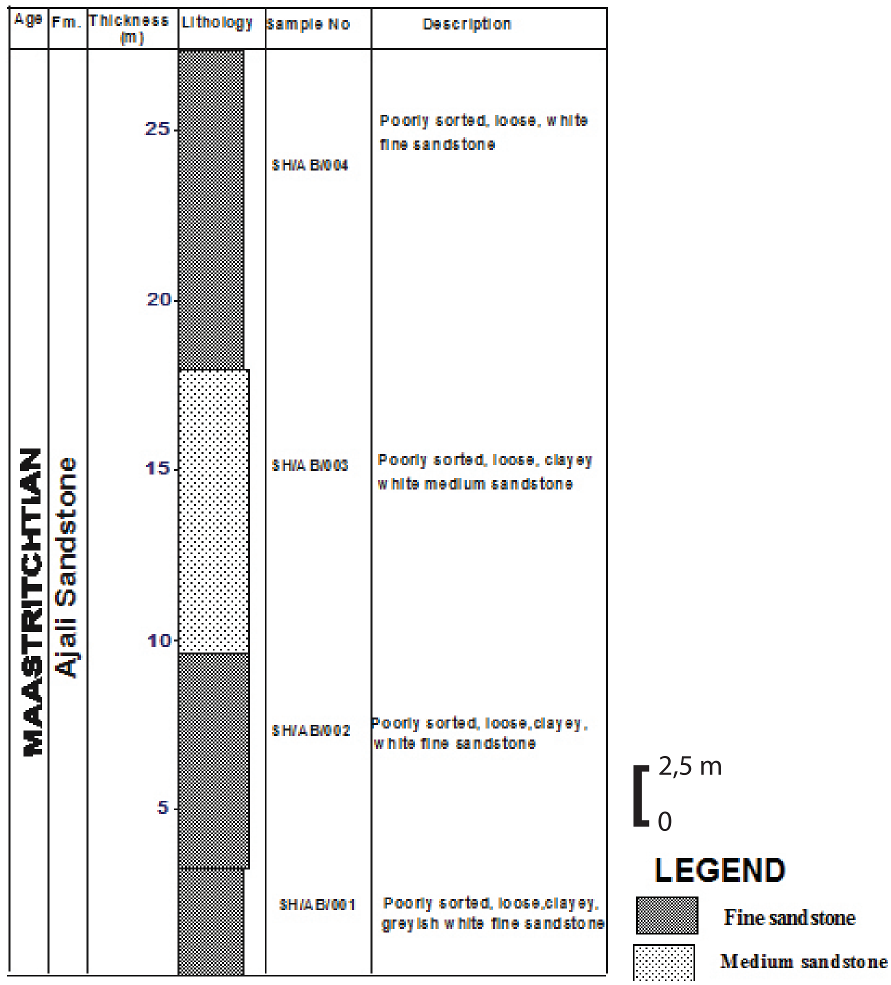


Figure 8: *Lithologic section of Ajali Sandstone exposed at Abor, Enugu. Co-ordinate: 6°21′ N and 7°24′ E.*

Location 7

This location represents an exposure of Ajali Sandstone at Abor. The overall sequence is 27 m thick (Figure 8), and its lateral extent is about 400 m. The base is made up of poorly sorted, loose, clayey, grey – white, fine grained sandstone of about 3 m thick. It trends 163° with dip amount of 8°. It is succeeded by poorly sorted, clayey, loose, clayey white sandstone of about 6.8 m, trending 3°, and dip direction of 210° S and dip amount of 6°. This is successively overlain by 7.8 m thick, poorly sorted, loose, clayey, white medium grained sandstone. It trends 10° with dip direction of 150° S and dip amount of 6°. This is succeeded by poorly sorted, loose, white fine grained sandstone (2 m), trending 5° with dipping direction of 220° S and dip amount of 6°.

Analytical methods

Grain size analysis

Twenty eight (28) representative sandstone samples were selected to be disaggregated for grain size studies. 100 g of each disaggregated sample was measured out and subjected to standard grain size analysis using a set of sieves at ½ phi interval and sieved on a Ro-tap shaker for fifteen minutes. Cumulative plots were drawn for each sample and statistical parameters were computed based on the concept of Folk (1974). The analysis was conducted at the Sedimentological Laboratory, University of Ibadan, Nigeria.

Paleocurrent analysis

Rosette diagrams were constructed and Mean Vector Azimuths (MVA) (Turker, 1996) were calculated based on dips and azimuths of planar cross bedding earlier taken in the field. The formula for calculating the mean vector azimuth is stated below:

$MVA = \tan^{-1} (\Sigma n \sin \sigma)/(\Sigma n \cos \sigma)$
Where σ is the azimuth in degree

Heavy mineral studies

5 g each of sandstone samples was subjected to heavy mineral analysis. Bromoform extracts of heavy minerals from 26 sandstones samples were rinsed with acetone and later mounted on slides. Point counting method of the non-opaque assemblages was done in the Petrology Laboratory, University of Ibadan, using a binocular petrological microscope. Photomicrographs of salient features were taken.

Thin section petrography

Twenty (20) sandstones samples were impregnated in resin and thin sectioned by standard methods. The slides preparations were done at the Department of Geology and Mineral Sciences, University of Ilorin. Petrographic examination, entailing point counting of the minerals, was carried out using a petrological microscope Model Brunel, at the Petrology Laboratory, University of Ibadan, Nigeria. This study is based on the concepts of Dickinson (1970) and Ingersoll et al. (1984).

TOC and Rock-Eval pyrolysis analyses

A total of ten (10) shale samples were pulverized and sieved through 0.2 mm sieve. 100 mg of each sieved sample was treated in concentrated HCl, to remove carbonates. The acid was drained off with a filtration apparatus fitted with a glass microfiber film. The filtrate was placed in a LECO crucible and dried at 110 °C for a minimum of 1 h. Later, each sample was analyzed with a LECO 600 Carbon Analyser for TOC determination.
Arising from TOC adequacy, 80 mg of each pulverized shale sample was heated in an inert atmosphere to determine the S1, S2 and S3 groups of compounds which were measured as peaks. Samples were heated at 300 °C for 3–5 min, to produce S1 peak by vaporizing the free hydrocarbons. The temperature of the oven was then increased by 25 °C/min to 600 °C, and the S2 and S3 peaks were measured from the pyrolytic degradation of the kerogen in the sample.
The analysis was determined by Rock-Eval II pyroanalyser which has a TOC module. These analyses were carried out at State Key Geochemistry Laboratory, China. The work flow pattern for the study is shown in Figure 9. Details of the analytical procedures can be found in Bankole (2011).

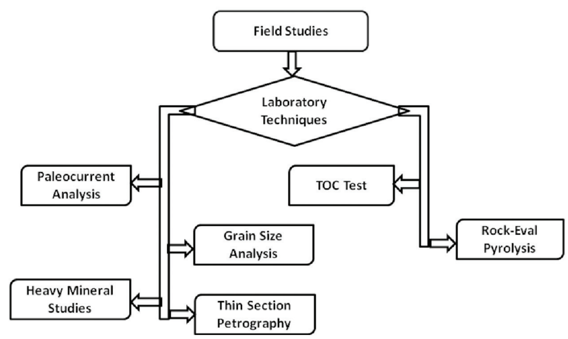


Figure 9: *Flow Chart of Laboratory Analyses.*

Results and discussion

Grain size characteristics

The results of the statistical parameters are presented in Table 1. The sandstone units of the Nkporo Formation are medium to coarse grained, poorly sorted to moderately well sorted, very negatively skewed to positively skewed and very leptokurtic to very platykurtic (Table 1). The Owelli Sandstones are medium to coarse grained, poorly sorted to moderately well sorted, negatively skewed to positively skewed and very leptokurtic to platykurtic (Table 1). The sandstone facies of the Mamu Formation is fine grained, moderately sorted to well sorted, negatively skewed and very leptokurtic. The Ajali Sandstone is medium to coarse grained, poorly sorted to moderately well sorted, negatively skewed to nearly symmetrical and leptokurtic to mesokurtic. Typical grain size probability plots for some samples (Figure 10) contain the upper two segments of a normal three segmented classes of suspension, saltation and bed load, and indicate fluvial setting (Visher, 1969).
Bivariate plots of the grain size parameters such as mean size vs. sorting (Friedman, 1961;

Moiola & Weiser, 1968), sorting vs. median (Stewart, 1958; Moiola & Weiser, 1968) are shown in Figure 11 and Figure 12, respectively. These show that the sediments are mainly product of river processes. Arising from linear discriminant function after Sahu (1964) which is presented in Table 2, it can be seen that the sediments were deposited in shallow marine to fluvial (deltaic) environment.

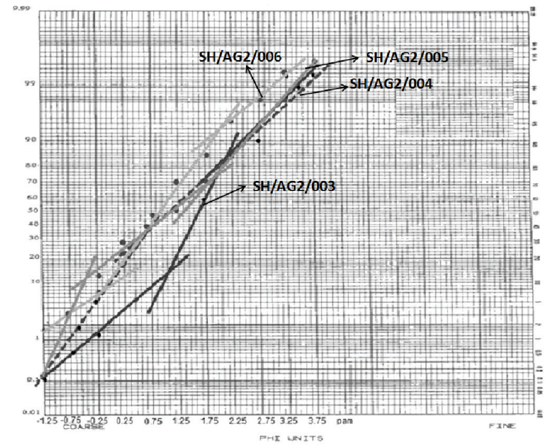


Figure10: *Typical probability plots for some studied sandstone samples.*

Table 1: *Summary of grain size parameters*

Size Parameter	Range (ϕ)	Average Value (ϕ)	Interpretation	Standard deviation
AJALI SANDSTONE (7 samples)				
Median	1.00–1.60	1.24	Medium to coarse grained	0.19
Mean	0.92–1.58	1.16	Medium to coarse grained	0.21
Sorting	0.55–1.06	0.86	Poorly sorted to moderately sorted	0.15
Skewness	−0.29–0.03	−0.12	Negatively skewed to nearly symmetrical	0.12
Kurtosis	0.96–1.43	1.14	Leptokurtic to mesokurtic	0.15
MAMU FORMATION (4 samples)				
Median	2.40–2.95	2.66	Fine grained	0.28
Mean	2.28–2.93	2.60	Fine grained	0.30
Sorting	0.46–0.84	0.64	Moderately sorted to well sorted	0.17
Skewness	−0.29–(−0.20)	−0.25	Negatively skewed	0.04
Kurtosis	1.51–2.09	1.79	Very leptokurtic	0.28
OWELLI SANDSTONE (7 samples)				
Median	0.5–1.35	0.94	Medium grained to coarse grained	0.32
Mean	0.08–1.38	0.86	Medium grained to coarse grained	0.43
Sorting	0.69–1.08	0.89	Poorly sorted to moderately sorted	0.15
Skewness	−0.31–0.19	−0.08	Negatively skewed to positively skewed	0.16
Kurtosis	0.77–1.70	1.12	Leptokurtic to platykurtic	0.28
NKPORO FORMATION (10 samples)				
Median	0.25–1.45	1.00	Medium to coarse grained	0.38
Mean	0.50–1.42	1.01	Medium to coarse grained	0.34
Sorting	0.50–1.03	0.82	Poorly sorted to moderately well sorted	0.20
Skewness	−0.44–0.18	−0.02	Very negatively skewed to Positively skewed	0.21
Kurtosis	0.00–1.74	1.05	Leptokurtic to Very kurtic	0.46

Table 2: *Deduced depositional environments based on linear discriminant function (after Sahu 1964)*

Sample No	Formation	Location	Calculated values	Interpretation
SH/NG/001	Ajali Sandstone	Ngwo	−2.52	Shallow marine
SH/NG/002			−6.58	Shallow marine
SH/NG/003			−6.06	Shallow marine
SH/AB/001		Abor	−6.65	Shallow marine
SH/AB/002			−7.76	Fluvial
SH/AB/003			−8.73	Fluvial
SH/AB/004			−10.44	Fluvial
SH/MA1/005	Mamu Fm.	Onyeama	−2.09	Shallow marine
SH/MA1/007			−2.70	Shallow marine
SH/MA1/008			−4.93	Shallow marine
SH/MA2/004		Proda	−6.83	Shallow marine
SH/AG/009	Owelli Sandstone	Agbogugu	−7.89	Fluvial
SH/AG/010			−6.49	Shallow marine
SH/AG/011			−3.52	Shallow marine
SH/AG/012			−7.44	Fluvial
SH/AG/013			−10.57	Fluvial
SH/AG/014			−5.00	Shallow marine
SH/AG/015			−8.07	Fluvial
SH/LE/003	Nkporo Formation	Leru	−6.92	Shallow marine
SH/LE/009			−7.44	Fluvial
SH/LE/010			−4.50	Shallow marine
SH/LE/011			−4.38	Shallow marine
SH/LE/012			−8.23	Fluvial
SH/LE/014			−10.09	Fluvial
SH/LE/016			−3.93	Shallow marine
SH/LE/017			−7.05	Shallow marine
SH/LE/020			−7.46	Fluvial
SH/LE/022			−0.89	Shallow marine

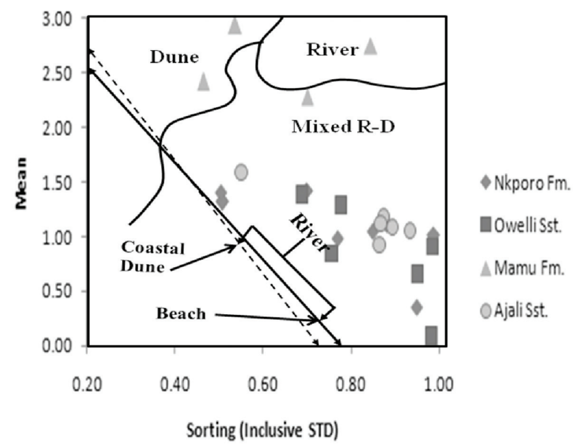


Figure 11: *Bivariant plot of grain size mean against sorting (inclusive standard deviation) after Friedman (1961), Moiola & Weiser (1968).*

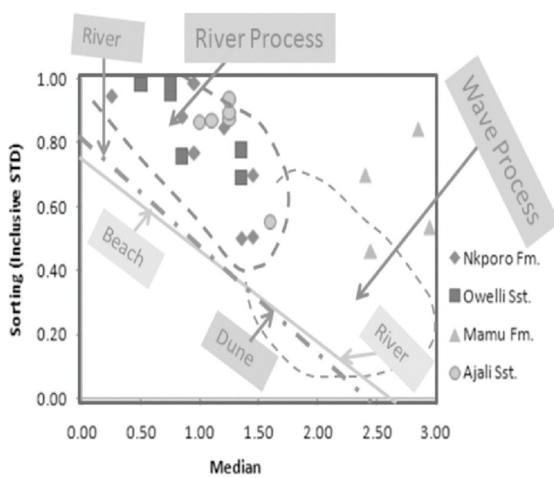


Figure 12: *Bivariant plot of grain size sorting (inclusive standard deviation) against median after Stewart (1958), Moiola & Weiser (1968).*

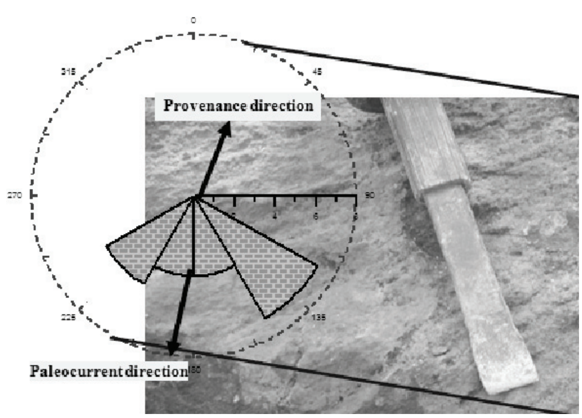


Figure 13: *Rosette diagram for Nkporo Formation exposed at Leru village (note the paleocurrent and provenance directions).*

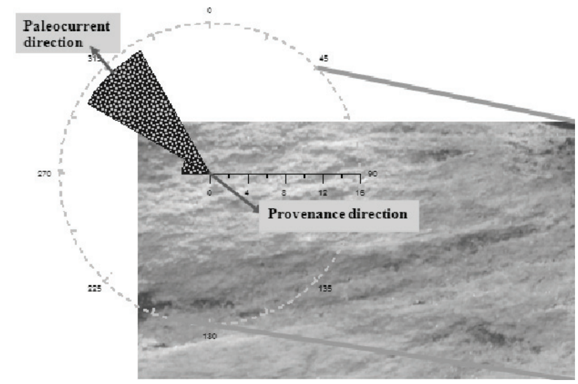


Figure 14: *Rosette diagram for Owelli Sandstone exposed at Agbogugu junction (note the paleocurrent and provenance directions).*

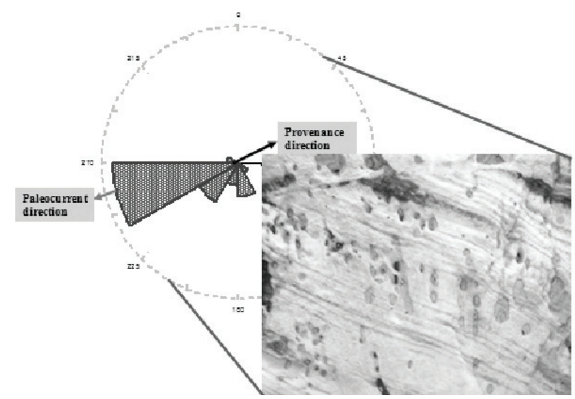


Figure 15: *Rosette diagram for Ajali Sandstone exposed at Ngwo (note the paleocurrent direction and the provenance direction).*

Provenance

Paleocurrent analysis gives the following mean vector azimuths of 225°, 315° and 234° for Nkporo, Owelli, and Ajali Sandstone, respectively. The mean vector azimuths and the rose diagrams suggest that the source of the sediments is confined to the northeast with little contribution from southeastern part of the basin (Figures 13–15).

The presence of zircon, rutile, tourmaline, garnet, apatite, kyanite, sillimanite, and staurolite in the heavy mineral suites (Table 3) also revealed that the sediments were derived from basement complex of both igneous and metamorphic origin (Feo-Codecido, 1956). The zircon, tourmaline, rutile (ZTR) index (Hubbert, 1962) ranges between 58 % and 75 % and indicates fairly mineralogically matured sediments. The sandstone petrography (Table 4) revealed quartz arenite with quartz being the main constituent (> 95 %), low feldspar and low lithic fragment contents (Figure 16). This suggest that the sediments have been subjected to intense weathering, prolonged transportation and/or have been reworked or recycled (Pettijohn et al., 1973; Akarish & El-Gohary, 2008).

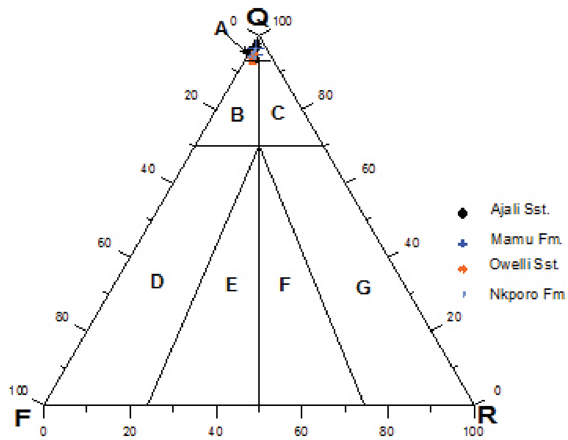
Paleoclimatic and Paleotectonic Deductions

Suttner et al. (1981) utilized Quartz, Feldspar and Rock Fragment (QFR) ternary plot to separate climatically induced compositional differences in Holocene sands. Based on their concept, the sandstones of Anambra Basin (Figure 17) were sourced from a metamorphic humid climatic setting, probably during the Campanian to Maastrichtian times. According to Dickinson & Suczek (1979), the detrital framework mode of sandstone composition is a function of the plate tectonic setting of the provenance. The QFR diagram based on this concept shows that the sandstones plotted within the rifted and uplifted continental block setting (Figure 18). This corresponds with the findings of Olade (1975), who posited that the Nigerian basement was domed and rifted in the pre-Early Cretaceous times to form the ensialic Benue aulacogen.

Table 3: *Heavy mineral assemblages (%) of the sandstone facies of the studied sediments*

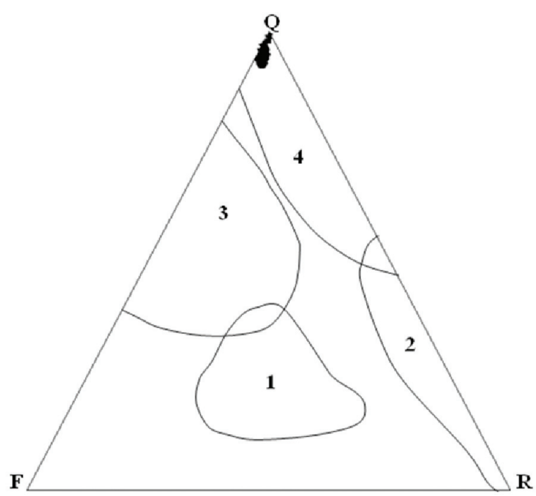
Formation	Location	Sample No	Z	T	R	K	St	Si	G	Ap	ZTR
Ajali Sandstone	Ngwo	SH/NG/001	8	6	7	-	3	-	5	-	72
		SH/NG/002	10	9	13	-	5	2	7	1	68
		SH/NG/003	13	9	10	4	4	3	6	2	63
	Abor	SH/AB/001	25	18	20	10	11	8	7	2	62
		SH/AB/002	12	14	10	5	6	4	5	1	63
		SH/AB/003	14	13	10	5	8	2	1	-	60
		SH/AB/004	20	18	19	5	10	5	6	-	69
Mamu Formation	Onyeama	SH/MA1/005	12	8	9	4	7	3	7	1	57
	Proda	SH/MA2/004	10	7	8	3	4	2	6	1	61
Owelli Sandstone	Agbogugu	SH/AG2/001	11	9	13	-	6	-	5	-	75
		SH/AG2/002	9	8	6	-	4	-	6	1	68
		SH/AG2/004	12	14	10	6	7	4	7	-	60
		SH/AG2/005	8	7	6	-	3	4	7	-	60
		SH/AG2/006	7	8	9	-	4	-	5	-	73
		SH/AG2/007	10	7	8	3	5	3	6	2	57
Nkporo Formation	Leru	SH/LE/003	11	8	14	2	8	-	9	2	61
		SH/LE/009	11	8	12	-	7	-	3	4	69
		SH/LE/010	14	10	11	3	5	3	4	3	66
		SH/LE/011	9	8	10	-	4	4	5	2	64
		SH/LE/012	13	12	10	3	6	5	5	4	60
		SH/LE/013	11	8	14	2	8	-	9	2	61
		SH/LE/014	16	13	26	10	14	7	8	5	56
		SH/LE/016	10	9	13	5	7	6	8	3	52
		SH/LE/017	18	10	12	4	3	4	6	-	70
		SH/LE/020	15	9	10	3	5	3	7	2	63
		SH/LE/022	20	18	19	8	12	10	10	1	58

**Z = Zircon, R = Rutile, T = Tourmaline, K = Kyanite, St = Staurolite, Si = Sillimanite, G = Garnet, Ap = Apatite*



A = Quartz arenite
B = Subarkose
C = Sublitharenite
D = Arkose
E = Feldspathic Litharkose
F = Feldspathic Litharenite
G = Litharenite
Q = Quartz (Framework Component)
F = Feldspar (Framework Component)
R = Rock Fragment (Framework Component)

Figure 16: *Ternary classification of sandstones based on framework components (after Folk, 1974).*



1 = Humid Plutonic Arid
2 = Metamorphic Arid
3 = Plutonic Humid
4 = Metamorphic Humid

Figure 17: *Ternary plot of QRF showing the paleoclimatic setting of the different formations (after Suttner et al., 1981).*

Hydrocarbon Potential
Organic matter quantity

The results of organic geochemical parameters are shown in Table 5. The shaley facies of Nkporo Formation have TOC values ranging between mass fractions 0.89 % and 3.59 % (av. 2.4 %, Table 5); the shale sequence of Owelli Formation have between 0.96 % and 1.17 % TOC while that of Enugu Shale has TOC range between 2.09 % and 3.98 % The value for Mamu Formation is 2.63 % TOC. These values imply that the organic matter content is adequate for hydrocarbon generation (Tissot & Welte, 1984) and can further be categorized as good to very good source rocks (Peters, 1986).

The values of the source potential (S1 + S2) of the samples range generally from 0.28 mg to 4.18 mg HC in 1 g rock, while the values of S2 ranges from 0.28 mg to 4.13 mg HC in g rock (Table 5). These values are indicative of insignificant oil rich source rocks but of gas generative potential (Peters, 1986). The source potential values (S1 + S2) of samples SH/LE/008 and SH/LE/021 are respectively 4.18 mg HC in 1 g TOC and 4.08 mg HC in g TOC for the Nkporo Formation and a value of 3.0 mg HC in 1 g TOC (SH/EN/007) for the Enugu Shale. The corresponding values for hydrocarbon yield (S2) for the same samples are (4.13, 4.04 and 2.97) mg

Table 4: *Thin section petrographic data for different sandstone facies*

Formation	Location	Sample No	Qm (%)	Qp (%)	Qt = Qm + Qp (%)	F (%)	Lt (%)
Ajali Sandstone	Ngwo	SH/NG/001	80.0	15.0	95.0	4.5	0.5
		SH/NG/002	87.0	9.0	96.0	3.8	0.2
		SH/NG/003	83.0	15.0	98.0	1.5	0.5
	Abor	SH/AB/001	90.0	7.0	97.0	2.0	1.0
		SH/AB/002	82.0	14.0	96.0	3.4	0.6
		SH/AB/003	79.0	15.0	94.0	4.3	1.7
		SH/AB/004	83.5	10.0	93.5	4.0	2.5
Mamu Formation	Onyeama	SH/MA1/005	79.3	15.7	95.0	3.6	1.4
	Proda	SH/MA2/004	84.0	12.8	96.8	2.2	1.0
Owelli Sandstone	Agbogugu	SH/AG/009	77.0	17.0	94.0	4.7	1.3
		SH/AG/010	76.4	19.0	95.4	3.2	1.4
		SH/AG/004	81.0	12.0	93.0	4.7	2.3
		SH/AG/013	79.0	14.0	93.0	5.0	2.0
		SH/AG/014	83.0	12.0	95.0	3.6	1.4
Nkporo Formation	Leru	SH/LE/009	74.0	19.0	93.0	4.5	2.5
		SH/LE/012	78.0	16.0	94.0	5.0	1.0
		SH/LE/014	85.0	10.0	95.0	3.8	1.2
		SH/LE/016	81.0	15.0	96.0	2.7	1.3
		SH/LE/017	75.6	18.0	93.6	4.3	2.1
		SH/LE/022	82.0	12.0	94.0	3.8	2.2

**Qm = Monocrystalline quartz; Qp = Polycrystalline quartz; F = Feldspar; Lt = Lithic fragment; Qt = total quartz.*

HC in g TOC. Such values according to Tissot & Welte, (1984) and Akande et al., (2005) indicate moderately rich source rocks with fair oil potential.

Type of Organic matter

The quality of organic matter content of a source rock determines the type of hydrocarbon generated (Tissot & Welte, 1984). Cross plots of hydrogen index versus T_{max} (Figure 19) and hydrogen index versus oxygen index (Figure 20) reveal Type III and Type IV kerogens. It is well known (e.g. van Krevellen, 1981) and many authors after him that type III kerogen is terrestrially derived, and dominated by vitrinite and lesser amount of inertinite (Nton et al., 2009) and produces less paraffinic oil. Though type III kerogen may contain terrestrially derived liptinite, but in an insignificant amount consisting of sporinite and resinite (e.g. Akande et al., 2005).

Peters (1986) suggested that at thermal maturity equivalent to a vitrinite reflectance of 0.6 % (T_{max} = 435 °C) , rocks with HI > 300 mg HC in 1 g TOC produce oil; those with HI between 150 mg HC/ in 1 g TOC and 300 mg HC in 1 g TOC produce oil and gas; those with HI between 50 mg HC/ in 1 g TOC and 150 mg HC/ in 1 g TOC produce gas and those with HI < 50 mg HC in 1 g TOC are inert. Arising from this study, only four samples: SH/MA/003 (Mamu Formation), SH/EN/007 (Enugu Shale), SH/LE/008 and SH/LE/021 (Nkporo Shale) contain HI between 50 mg HC in 1 g TOC and 150 mg HC in 1 g TOC. In actual fact, the T_{max} for the samples from Mamu Formation and Enugu shales are <435 °C which may not support this generalization. Therefore only two samples from Nkporo Shale (20 %) can be termed gas prone while the majority (80 %) are inert with HI < 50 mg HC in 1 g TOC.

Table 5: *Summary of the Rock-Eval pyrolysis parameters*

Sample No	Location	Formation	TOC (wt%)	S1	S2	S3	Tmax (°C)	Ro (%)	HI	OI	S2/S3	S1/TOC*100	S1+S2	PI
SH/MA/003	Onyeama	Mamu Formation	2.63	0.05	1.86	0.38	429	0.57	71	14	0.03	2	1.91	0.03
SH/EN/001	Enugu-Ont. Exp.Rd.	EnuguSh.	2.09	0.02	0.72	1.16	429	0.57	34	56	0.03	1	0.74	0.03
SH/EN/004			2.21	0.02	1.01	0.15	428	0.56	46	7	0.02	1	1.03	0.02
SH/EN/007			3.98	0.03	2.97	1.48	429	0.57	75	37	0.01	1	3.0	0.01
SH/AG/004	Agbogugu	Owelli Sandstone	1.17	0.01	0.37	1.56	439	0.76	32	133	0.03	1	0.38	0.03
SH/AG/005			0.96	0	0.28	0.74	444	0.85	29	77	0	0	0.28	0
SH/LE/002	Leru	Nkporo Formation	2.28	0.02	0.88	1.15	426	0.52	39	50	0.02	1	0.90	0.02
SH/LE/008			3.59	0.05	4.13	1.84	438	0.74	115	51	0.01	1	4.18	0.01
SH/LE/013			0.89	0.01	0.28	0.5	421	0.43	31	56	0.04	1	0.29	0.03
SH/LE/021			2.86	0.04	4.04	0	436	0.7	141	0	0.01	1	4.08	0.01

**Notes:*

TOC - total organic carbon, wt. %

S1 - volatile hydrocarbon (HC) content, mg HC/g rock

S2 - remaining HC generative potential, mg HC/g rock

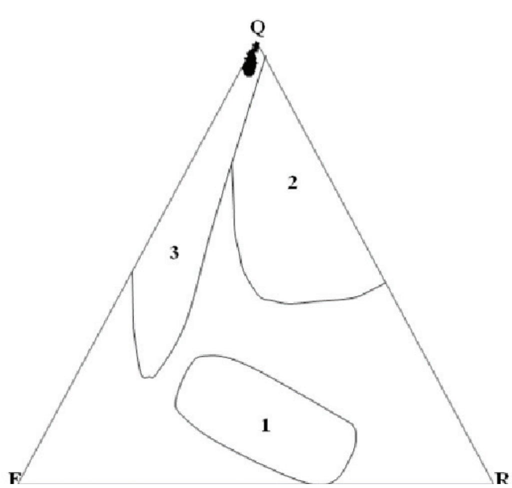
S3 - carbon dioxide content, mg CO_2/g rock

PI - Production index = S1/ (S2 + S2)

HI - Hydrogen Index = S2 × 100/TOC (mg HC in g rock)

OI - Oxygen index = S3 × 100/TOC, mg CO_2/g TOC

Cal. R0/% = 0.018 03 × T_{max} – 7.16



1 = Magmatic Arc Provenance
2 = Recycled Orogen Provenance
3 = Continental Block Provenance

Figure 18: *Ternary plot of QRF showing paleotectonic settings (after Dickinson & Suczek, 1979) for the different formations discussed in this paper.*

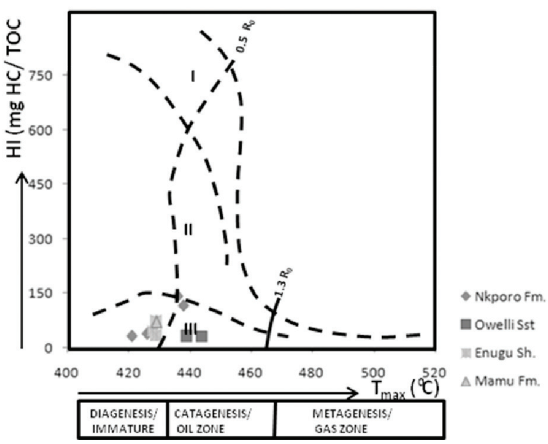


Figure 19: *Classification of Kerogens on the HI-Tmax (adapted from Akande et al., 2005).*

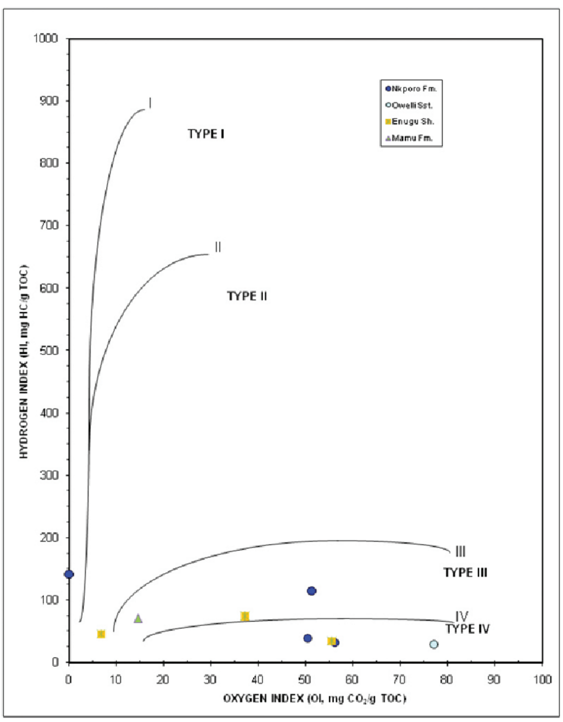


Figure 20: *Plot of HI versus OI indicating the kerogen types (Note that all treated samples are of the Types III/IV i.e. vitrinite/inertinite-rich type of kerogen).*

Maturity of the organic matter

Thermal maturity describes the extent of heat-driven reactions which convert sedimentary organic matter into petroleum (Peters & Moldowan, 1993). In general, the extent of maturity depends on the relation of organic matter to the oil generation window. The T_{max} is a thermal stress parameter, dependent primarily on time/temperature conditions and can only be approximately related to the stage of petroleum generation for the rock type.

The T_{max} values presented in Table 5 show that the sediments of Nkporo Formation have values between 421 °C and 444 °C, indicating immature to marginally mature organic matter. Arising from the low values of the hydrocarbon yield i.e. S2 (Table 5) maturity status based on the T_{max} appear unreliable in determining the maturity level. Based on the production index (PI) values range of between 0.00 and 0.03, it is quite certain that all the samples are thermally immature at the present level of consideration.

Summary and conclusions

Outcrop samples from road cut exposures within the Anambra basin were sampled from the respective formations namely; Nkporo Formation, Owelli Sandstone, Enugu Formation, Mamu Formation and Ajali Sandstone for sedimentological characteristics, provenance, palaeoclimatic and tectonic deductions as well as appraise aspects of the hydrocarbon potential. Textural characteristics show that the sandstones are mainly moderately sorted, coarse to nearly symmetrical and leptokurtic. Cross plots of statistical parameters show that the sandstones are mainly fluvial deposits. The sandstones are mature with quartz content ranging from 93.0–96.8 %; feldspars from 2.2 % to 5.0 % while rock fragments are from 0.2–2.5 % and classify the treated sandstones as quartz arenites. Heavy mineral assemblages include zircon, tourmaline, garnet, apatite and rutile with ZTR maturity index ranging from 60 to 72 % (Ajali Sandstone); 57–61 % (Mamu Formation), 57–73 % (Owelli Sandstone) and 52–70 % (Nkporo Formation). These indicate a source in basement rocks, mainly the metamorphic and igneous rocks sourced from the Adamawa-Abakaliki folded belt and Oban massif which were rifted, uplifted and within a humid climatic setting.

Organic matter content is adequate, immature with Types III and IV kerogen that indicate terrestrial derivation. It is envisaged that there is the possibility of securing mature sediments with moderate oil potential at depth, particularly within the Nkporo Shale and Enugu Shale.

Acknowledgements

The authors are grateful to the staff and management of State Key Laboratory of Organic Geochemistry, Chinese Academy of Science, Guangzhou, China, for assistance in laboratory analysis. The corresponding author also appreciates the cordial working relationship with colleagues and students at the Department of Geology, University of Ibadan, Nigeria.

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