Depositional Environments and Geochemical Assessments of the Bende Ameki Formation Potential as Petroleum Source Rocks in the Ogbunike Quarry, South-Eastern Nigeria

Olajubaje, T. A.,
Akande, S. O.,
Department of Geology and Mineral Sciences,
University of Ilorin, Ilorin, Nigeria
Adeoye, J. A.,
Department of Geosciences, Mountain Top University, Ibafo, Nigeria
Adekeye, O. A.,
Department of Geology and Mineral Sciences,
University of Ilorin, Ilorin, Nigeria
Friedrich, C.
West Sam Houston Parkway North, Houston TX, USA

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Abstract

This paper focuses on investigating the paleoenvironments and hydrocarbon generation potentials of the outcropping Eocene Bende-Ameki Formation at Ogbunike quarry, Anambra Basin southeastern Nigeria, which is the Niger Delta Agbada Formation subsurface equivalent. The fine to coarse sandstones interbedded with parallel laminated grey, coaly shales, and bioturbated claystones were the dominant rock facies. The shales contain *Ammobaculities, Ammontium, lenticulina, and Reophax* benthic foraminifera of brackish to outer shelf environments. The rock sequence and biofacies associations indicate a fluvial, shoreface to delta environments. The marine and continental paleoenvironments are supported by the concentration and association of redox-sensitive trace elements such as vanadium and nickel of oxic to dysoxic paleoconditions. The twenty shales have a range of TOC from 0.39 - 8.81 wt% (mean 2.2 2 wt%), suggesting a good to very good source rocks. The organic richness is highest within the depth of 2 – 6 m across the quarry. Their genetic potential (S_1+S_2) ranges from 0.22 - 27.35 (mean 2.8 kgHC/ton) of rock, and hydrogen index from 26 to 292 mgHC/gTOC with a mean of 67.3 mgHC/gTOC. This, however, indicates dominance of Type III gas prone kerogen of terrestrial origin. The oxygenated water column

characterized by the presence of benthonic scavengers may not preserve lipid-enriched organic constituents of anoxic paleoenvironments which could account for the rare Type II oil and gas prone kerogen in the source rock. The thermal history inferred from the Tmax between 401°C - 424°C suggests that the source rocks are immature at the present stratigraphic level.

Keywords: *Ogbunike, Anambra Basin, Eocene, Bende-Ameki, Source rock, Paleoenvironments*

Introduction

The 40,000 km^2 Anambra Basin in the southeastern Nigeria is bounded to the south by the Niger Delta hinge line and northwesterly by the Benue basins and Abakaliki fold belt to the southeast (Figure 1). It consists of about 6,000 m thick Cretaceous to Tertiary sedimentary rocks. It has been explored as far back as the early 60's with many exploratory wells drilled with some success. Neogene stratigraphic units are consequent to short periods of transgression and long period of regression responsible for cyclic pattern of the shales and sandstone facies which are traceable to the subsurface Niger Delta. The present study investigated the exposed Miocene ~~shales~~ shale beds located on the coordinate of 6^o 10'48" N and 6^{o}51'50"E at Ogbunike quarry, Anambra State southeastern Nigeria (Figure 2). The study seeks to report the paleoenvironments of the shale facies and its impact on their organic matter quality and quantity for hydrocarbon generation for the first time.

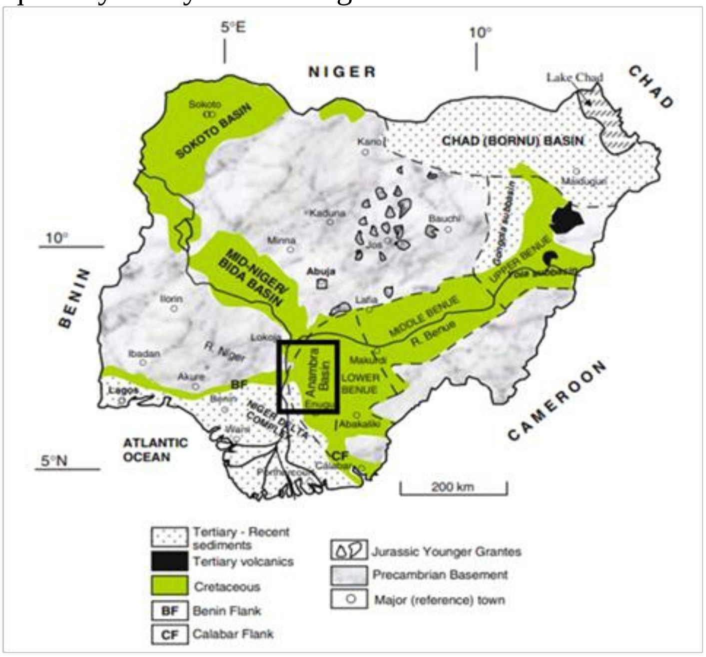

Figure 1. Generalized geological map of Nigeria showing the Anambra Basin in the thick rectangular box (modified after Obaje, 2004).

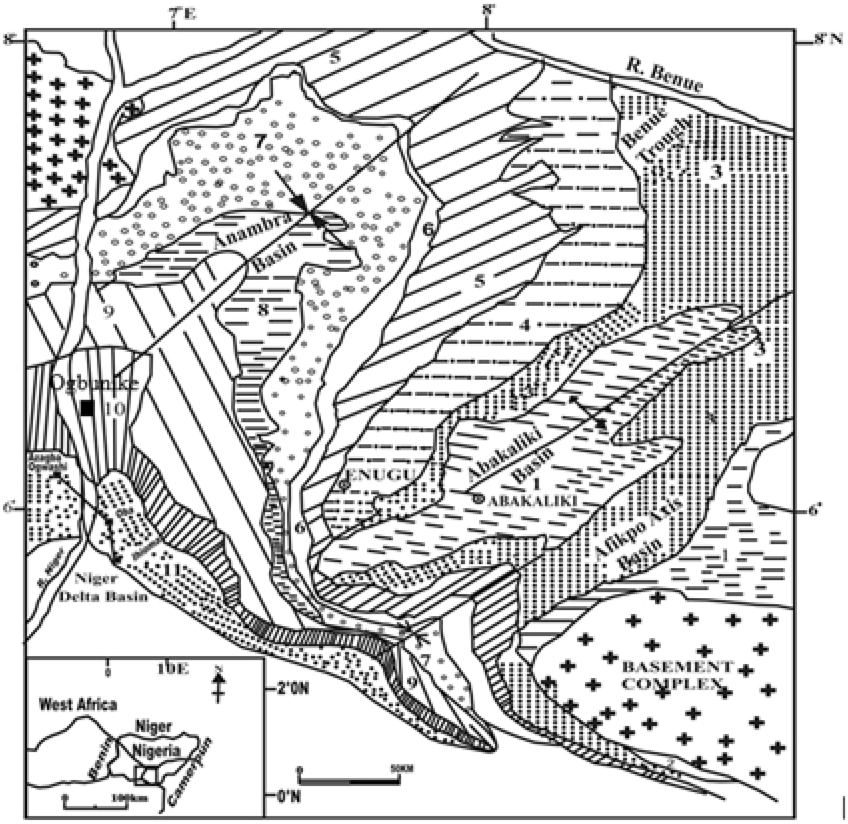

Figure 2. Generalized geological map of southern Benue Trough, Nigeria, showing the location of Ogbunike Quarry in black box (Modified after Akande et al., 2010)

Geology and Stratigraphy of Anambra Basin

The Benue Trough has been described as the failed arm among the successfully rifted areas of Gulf of Guinea and South Atlantic Ocean of the triple arm junction, along which spreading resulted in the Africa plate separating from the South America plate (Olade, 1975). The trough was stretched in a NE-SW direction resting unconformably upon the Precambrian crystalline basement. It is then geographically divided into northern, central, and southern Benue Trough. Southern Benue Trough consists of the oldest sediments of mid to late Cretaceous in Abakaliki Basin and post-Santonian to Neogene sediment in the Anambra Basin. The Abakaliki Basin's platform (Figure 2) was subsided during the Santonian tectonic events in the eastern part of the trough, displacing the depocentre to the west and northwest to form Anambra basin which received large volume of siliciclastic sediments (Murat, 1972). The resulting rock succession comprises of the Nkporo Group, Mamu Formation, Ajali Sandstone, Nsukka Formation, Imo Formation, and the Ameki Group (Figure 3). The third sedimentary phase, which initiated the formation of the petroliferous Niger Delta, commenced in the late Eocene as a result of a major earth movement that further structurally inverted the Abakaliki region and displaced the depositional axis further to the south of the Anambra Basin (Obi et al., 2001).

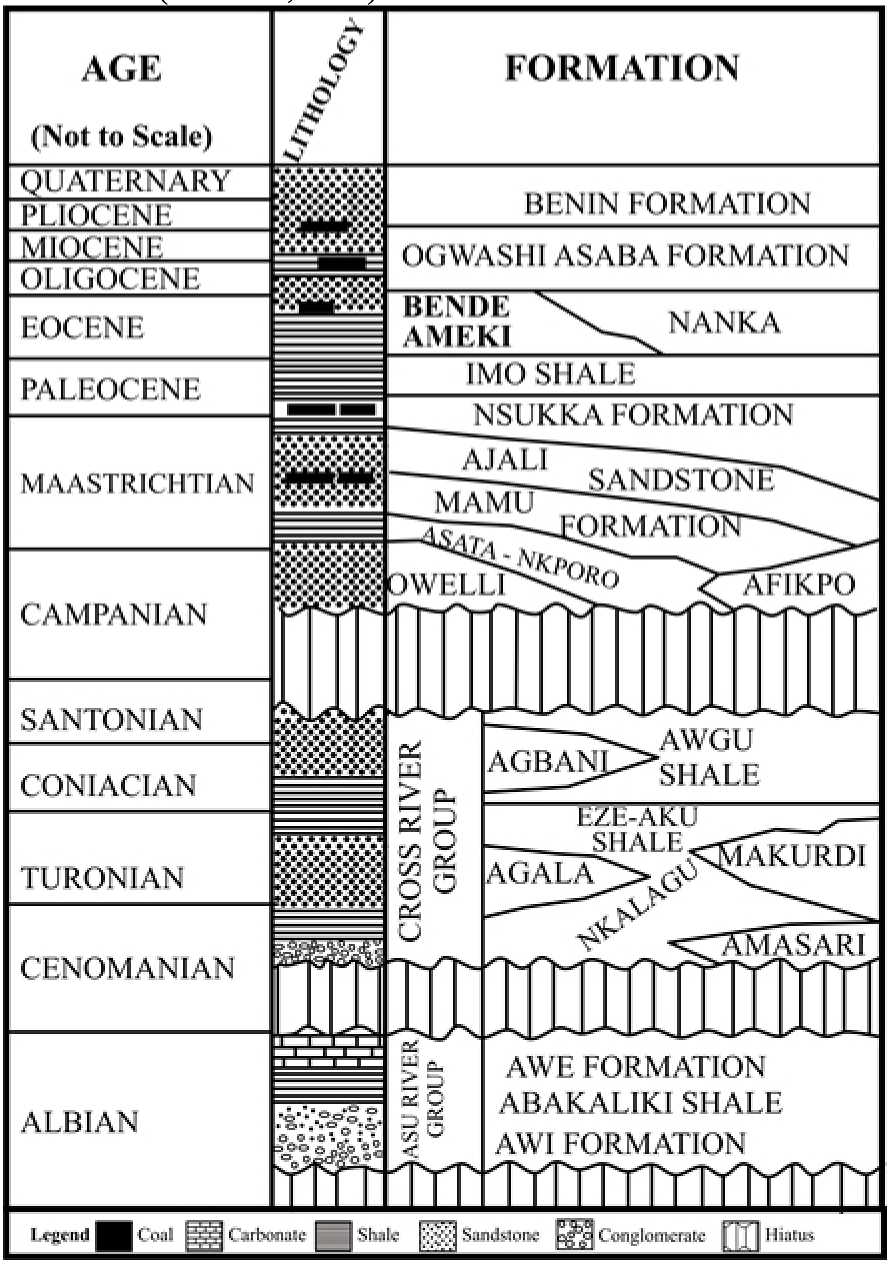

Figure 3. Stratigraphic and lithologic section of Lower Benue Trough and Anambra Basin (Modified after Akaegbobi et al., 2000)

Nkporo Formation (Campanian – Maastrichtian)

Nkporo Formation consists of a sequence of bluish to dark grey shale and mudstone which is locally with sandy shales, thin sandstones, and shelly limestone beds. The shaly facies grade laterally to sandstones of the Owelli and Afikpo Formations in the Anambra Basin.

Mamu Formation (Lower Maastrichtian)

The Mamu Formation consists of alternating sandstone, sandy shales, and mudstones with interbedded coal seams. The Formation is underlain by the Campanian Enugu/Nkporo shales (lateral equivalents) and Nsukka Formation (Upper Maastrichtian) to Danian. Five sedimentary units were recognized in the Mamu Formation in the Enugu area where the thickest exposed section (approximately 80m) occurs. The basal units consist of shale or sandy shale, sandstone with occasional shale beds, carbonaceous shale, coal seams, and sandy shale (Simpsons, 1954; Reyment, 1965) (Figure 3).

Ajali Formation

The Ajali sandstone overlies the Mamu Formation and it has a diachronous age from South to the North (middle – late Maastrichtian). In addition, it exhibits significant thickness variation from less than 300m to over 1000m at the centre of the basin. Depositional characteristics are uniform for most parts of the basin, and it is made up of textually mature sand facies i.e. mature quartz arenite intercalated with kaolinite beds (Figure 3).

Nsukka Formation

Nsukka Formation, which overlies the Ajali Sandstone, begins with coarse- to medium-grained sandstones and passes upward into well-bedded blue clays, fine-grained sandstones, and carbonaceous shales with thin bands of limestone (Reyment, 1965; Obi et al., 2001) (Figure 3).

The Imo Formation

The Imo Formation consists of blue-grey clays and black shales with bands of calcareous sandstones, marls, and limestone (Reyment, 1965). Ostracods and foraminifera biostratigraphy (Reyment, 1965), and microfauna recovered from the basal limestone unit (Adegoke et al., 1980; Arua, 1986), indicate a Paleocene age for the formation. The Imo Formation is the outcrop lithofacies equivalent of the Akata Formation in the subsurface Niger Delta (Short & Stauble, 1967; Avbovbo, 1978).

Ameki Group

The Ameki Group consists basically of the Nanka Sand, Nsugbe Formation, and Ameki Formation (Nwajide, 1979), which are laterally equivalents. The age of the formation has been considered to be either early Eocene (Reyment, 1965) or early to middle Eocene (Berggren, 1960; Adegoke, 1969). The depositional environment has been interpreted as estuarine, lagoonal, and open marine based on the faunal content. White (1926) interpreted an estuarine environment because of the presence of fish species of known estuarine affinity. Adegoke (1969), however, indicated that the fish were probably washed into the Ameki Sea from inland waters, and preferred an open marine depositional environment. Nwajide (1979) and Arua (1986) suggested environments that ranged from nearshore (barrier ridge-lagoonal complex) to intertidal and subtidal zones of the shelf environments. Furthermore, Fayose and Ola (1990) also reported that the sediments have marine inputs with waters depths of about 10 m and 100 m.

The Ogwashi-Asaba Formation

The Ogwashi-Asaba Formation comprises of alternating coarse-grained sandstone, lignite seams, and light coloured clays of continental origin (Kogbe, 1976). Reyment (1965) suggested an Oligocene-Miocene age for the formation, while Jan du Chene et al. (1978) reported middle Eocene age for the basal part from palynology. The Ameki Group and the Ogwashi- Asaba Formation are correlative with the Agbada Formation in the surface Niger Delta. Subsequently, Akande (1993, 1998) stated that there is increasing attention to the geochemistry of the southern Benue basins. Akande (2015) also reported that different methane precursors in the interbedded coal and shale lithologies suggest remarkable potential to contribute a mixture of hydrocarbons derived from marine and terrestrial organic matters. The coal and coaly shale are not within the thermally mature stratigraphic levels in the outcrop, but in the sub-surface level of Agbada formation. Hence, they are potential source rocks for hydrocarbons generation in the Niger Delta.

Methodology

The exposed rock units at the Ogbunike quarry have been described, sampled, and logged. Seventy seven (77) rock samples of varying facies including shale, sandstones, claystone, and siltstone were carefully sampled from four locations within the quarry. A total of twenty (20) samples of shale were collected, pulverized, and analyzed for Total Organic Carbon (TOC) by means of LECO-CS analyzer. Standard methods of pulverization and treatment with hydrochloric acid (HCl) for carbonate removal were employed.

This was before 100mg of each sample was measured and weighed. Twelve (12) shale samples were analyzed for their microfossil contents. 200g of each sample were weighed and dried so as to remove the moisture content in the shale. Solution of concentrated hydrogen peroxide (H_2O_2) was diluted with water in a ratio 1:3 i.e. 100ml of H_2O_2 reacting with 300ml of water. The solution was poured into the weighed shale sample which was already prepared in a container for digestion. The mixture was left for 24 hours for proper digestion after which washing was done using 0.063mm sieve under running water. The residues were air dried and stored carefully in well labelled sealed plastic bottles. Thus, this was followed by the picking, identification, and description of the foraminifera species under the binocular microscope. This was done to identify the species and their occurrence to enable depositional environment reconstruction.

The Rock-Eval pyrolysis technique of Espitalie (1977) provides data on the quantity, type, and thermal maturity of the associated organic matter for the twenty (20) shale samples. This was carried out at the Organic Geochemistry laboratory of Australian Laboratory Services (ALS), Empirical Laboratory Houston, Texas, USA. The samples were heated under an inert atmosphere of helium at 300º C for 3-4 min and then pyrolysed at 25º C/minute to 600º C, followed by posterior cooling down for the next sample to be run. The pyrolysis values obtained include Tmax, S_1, S_2, and S_3. These parameters were further used to evaluate the hydrogen index, oxygen index, production index which are indicative of the level of maturity of the organic matter, the type or types of organic matter, and the amount of hydrocarbons already produced or that can be produced from a studied rock sample.

The whole rock and trace elements analyses were carried out at Activation laboratory (Actlab) Ancaster, Ontario, Canada, on eleven (11) selected shale samples using ICP-OES and ICP-MS. This fusion technique involves a lithium metaborate /teraborate fusion. The fusion procedures consist of heating a mixture of sample and flux at high temperature (800-1200 ºC) so that the flux melts and the sample dissolves. The overall composition and cooling conditions is such that the end product after cooling is one phase glass. The resulting molten bead is rapidly digested in a weak nitric acid solution. The fusion ensures the entire sample is dissolved. For trace element analysis, 0.25 g of the sample was digested with four acids beginning with hydrofluoric, followed by a mixture of nitric and hydrochloric acids, heated using precise programmer controlled heating in several ramping and heating cycles which takes the samples to dryness. After dryness is attained, samples are brought back into the solution using hydrochloric acid. The sample solution was then analyzed for elemental concentration using Perkin Elmer Optima 3000 ICP. Calibration was performed using USGS and CANMET certified reference materials.

Results and Discussion
Depositional Environments Interpretation
Lithofacies and Sedimentology

The rock facies identified at the Ogbunike quarry are essentially sandstones, siltstones, shales, and claystone which are indicative of various depositional environments and conditions in the basin. The lithological sections were drawn and described at four locations labelled OB1, OB2, OB3, and OB4 along a depositional strike trending NW-SE in the quarry. In addition, distinct variations in the lithofacies were observed vertically up the section and horizontally along the bedding planes (Figure 4).

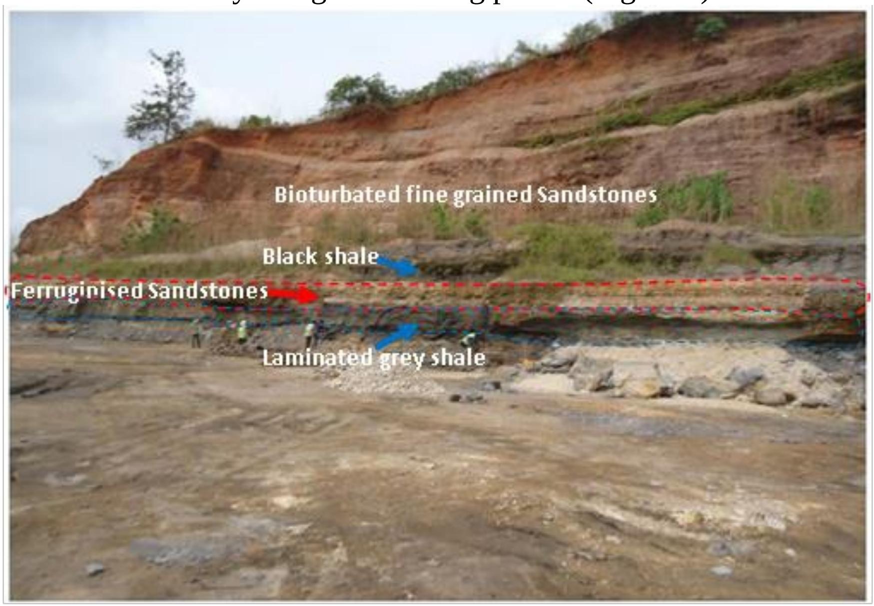

Figure 4. Field photograph of Bende - Ameki Formation exposed at Ogbunike quarry showing some of the lithofacies.

At location OB1 in the northernmost part of the quarry, the basal sandstone is medium grained and bioturbated overlained by a ferruginised fine grained facies. The bioturbation shows an intense oxidation before a transition into a parallel laminated dark grey shale overlained by highly ferruginised bioturbated claystone and capped by ferruginised sandstones. The above described sedimentation pattern at location OB1 was observed in all the locations except that at location 2 (OB2) and 3 (OB3) (Figure 5). Here, the thickest sections which exist have more of laminated dark to black coaly shales. The parallel laminated features of the shales suggest possible water stratification during the period of quietness in the basin. The lamination shows that the effect of tide, waves or other high energy related agent of deposition, are minimal. Also, a relatively deep-water environment, which may not be well sustained, prevailed. The features suggest a lagoonal and swamps depositional environments passing into open shelf facies.

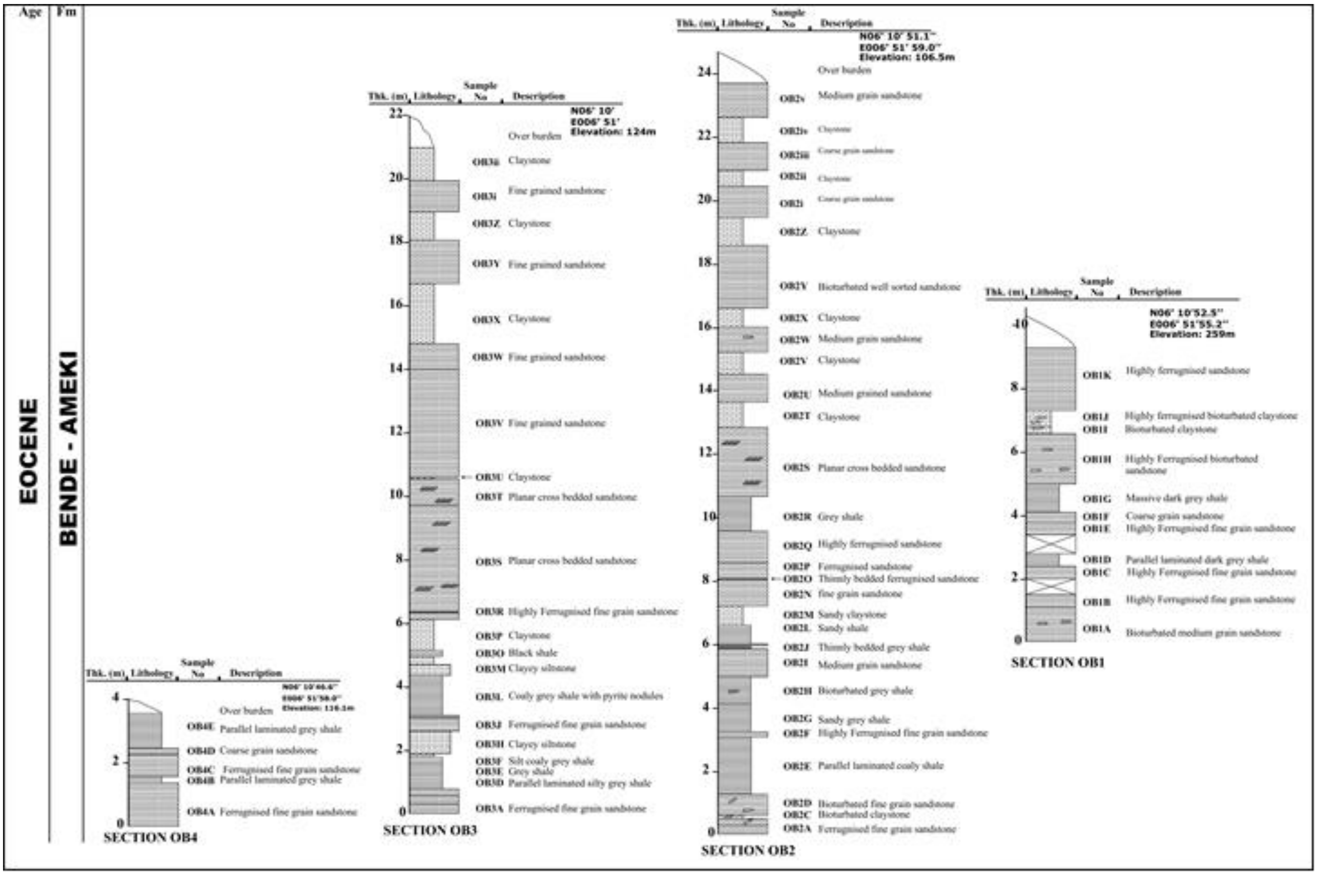

Figure 5. Composite lithologic sections of the Bende - Ameki Formation exposed at Ogbunike

Benthic Foraminifera Occurrence

Benthic foraminifera of the *Ammobaculites*, *Amotium*, *Buliamina*, *Lenticulina*, *Reophax* and *Textularian* genus were found in the shale. They are few with low diversity and small sized body structure which is commonly attributed to a harsh or unconducive environmental conditions as well as insufficient nutrient to support large population. The *Ammobaculites* being an infaunal deposit feeder is commonly found in long range habitat from marsh, estuaries, brackish to neritic, and bathyal environments. However, they can tolerate low oxygen levels (Culver & Buzas, 1981; Koutsoukos et al., 1990; Murray, 1991). Ammotium are generally restricted to shallow brackish waters (Murray, 1968, 1991; Bronnimann, 1992). *Lenticulina* prefers cool marine conditions on the outer shelf to bathyal depth (Murray, 1991). They are indicative of high phytodetritus influx and dysoxic bottom water, an indication of marine influences to the organic matter constituents of the shale, which can enhance its potential as hydrocarbon source rocks.

Trace Elements

The relative abundance of trace elements and oxides in sediment is controlled by sedimentation rate, terrigenous influx, biogenic influx, hydrothermal input, diagenesis and, ultimately, weathering (Leventhal, 1998; Schieber & Zimmerle, 1998). Their enrichments can lead to understanding of their paleo-depositional and paleo redox setting, as well as the paleo-climate (Vine & Tourtelot, 1970). The pH and Eh conditions has a significant impact on the environments as those sensitive to redox conditions are more soluble under oxidizing conditions and are less soluble under reducing conditions. Therefore, the concentration of these redox-sensitive elements, such as V, Ni, Cu, Cr Mo, and Co (Table 1), were sensitive indicators of prevalence paleoconditions (Adegoke et al., 2014). The concentration of vanadium (V), and nickel (Ni) as well as their ratios provide a means of determining the degree of anoxia during deposition (Barwise, 1990; Bechtel et al., 2001; Galarraga et al., 2008). Vanadium is usually enriched in comparison with Ni in anoxic marine environments (Peters & Moldowan, 1993). This is due to strong activities of the sulfate reduction bacteria in this environment and greater relative stability of vanadyl versus nickel porphyrin complexes. The reverse is the case under normal oxic conditions (Lewan, 1984).

Table 1. Trace elements concentration in ppm of shales from Ogbunike

Samples	V	Cr	Ni	Cu	Zn	Ba	V/Cr	Co	Ni/Co	V/Ni	V/(V + Ni)	V + Ni	V/Cr
OB1D	90	130	42	15	31	427	0.69	14	3.00	2.14	0.68	132	0.69
OB1G B	103	140	52	17	31	559	0.74	21	2.48	1.98	0.66	155	0.74
OB1G M	116	150	69	18	37	714	0.77	29	2.38	1.68	0.63	185	0.77
OB1G T	99	150	72	26	33	787	0.66	39	1.85	1.38	0.58	171	0.66
OB2E	103	130	36	11	26	743	0.79	15	2.40	2.86	0.74	139	0.79
OB2G	35	30	16	10	14	592	1.17	5	3.20	2.19	0.69	51	1.17
OB2H B	142	140	63	16	106	648	1.01	34	1.85	2.25	0.69	205	1.01
OB2R M	152	160	89	22	130	357	0.95	42	2.12	1.71	0.63	241	0.95
OB3F	84	90	44	10	209	881	0.93	21	2.10	1.91	0.66	128	0.93
OB3O	139	140	65	23	55	204	0.99	29	2.24	2.14	0.68	204	0.99
OB4E	115	140	51	14	132	917	0.82	21	2.43	2.25	0.69	166	0.82

According to Galarraga et al. (2008), a V/Ni ratio greater than 3 suggest that the organic matter were deposited in a reducing environment, while V/Ni ratios ranging from 1.9 to 3 ppm indicates dysoxic–oxic conditions. The distribution of the trace elements in the investigated shales revealed that vanadium ion concentrations are generally more than the concentrations of nickel ion. The V/Ni ration ranging between 1.91 – 2.86 was observed in eight (8) of the black shales, while the remaining three were below 1.9, thus suggesting that they are mixed marine and terrigenous organic matter under dysoxic to oxic conditions (Figure 6). Adegoke et al. (2014) reported V/(V + Ni) value of 0.69 – 0.76 ppm in the Gongila shale, Chad Basin, in the northeastern Nigeria indicating that they might have been deposited in a dysoxic environment. This occurrence is similar to the observed values of 0.68 – 0.74 from the Ogbunike shales, while some interbeding units have values lower than the bench mark suggesting the contributions of an oxidizing conditions at such intervals.

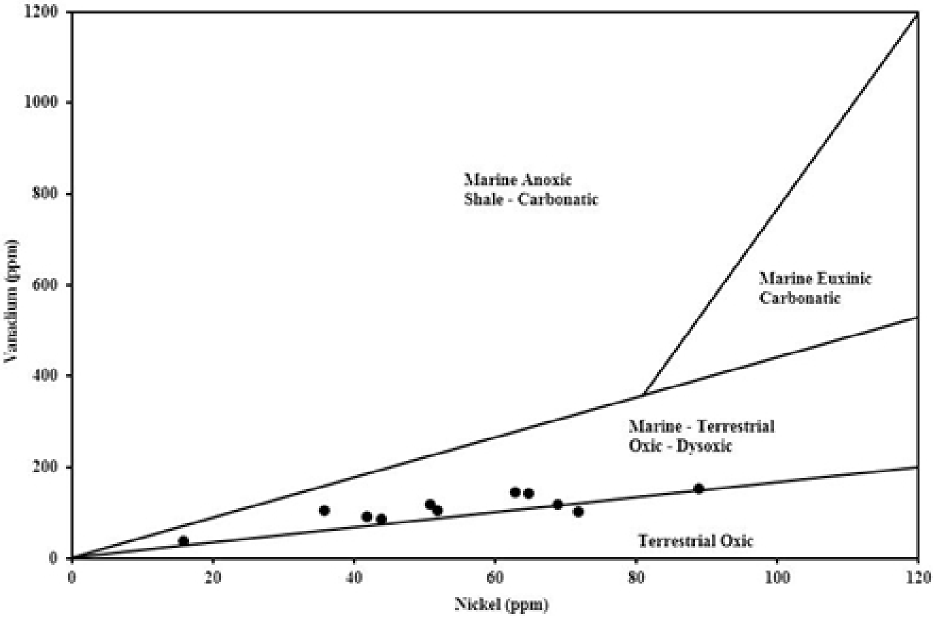

Figure 6. Cross plot of vanadium versus nickel of shale samples from Ogbunike quarry, Anambra Basin, showing that the organic matter had mixed marine and terrigenous source input and were deposited under oxic - dysoxic conditions (modified after Galarraga et al., 2008).

Similarly, the V/Cr ratio has been used as a paleo-oxygenation indicator in a number of studies. Values of V/Cr >2 are thought to represent anoxic depositional conditions, whereas values below 2 are indicative of more oxidizing conditions (Dill et al., 1988). The shales have V/Cr values (Table 1), which may indicate that relatively oxidizing conditions was also prevalent. In addition, a Ni/Co ratio above 5 indicates dysoxic to anoxic environment, whereas a ratio below 5 suggests an oxic environment (Jones & Manning, 1994). All the shales have Ni/Co ratio below 5, which suggests prevailing oxidizing conditions.

Petroleum Potentials

The total organic carbon of the twenty (20) shales range from 0.39 – 8.81 wt% with an average value of 2.3 wt%. Generally, most of the shales have TOC value 1.0 wt% which depicts a good to very good source rock (Peter & Cassa, 1994). The TOC concentration correlates with the lithofacies in such a way that the 0.39 wt% was from the sandy shale units, while the remaining nineteen samples which represent 95 % of the shales have TOC values greater than 1.1 wt%. The laminated greyish to black shales have TOC values in the range 3.15 to 8.18 wt % that occurs within the base of the section within 2m to 6m depth across the quarry. The organic carbon in the sediments alone can only identify potential oil source beds. If it is hydrogen poor, it will be gas prone or inert, and without any significant oil generating potential (Tissot et al., 1974; Demaison & Moore, 1980).

The type of hydrocarbons a source rock can generate is dependent on its kerogen constituents. Kerogen have been classified into four types based on their hydrogen indices (HI), which is the derivative of S_2 and TOC, which is proportional to the amount of hydrogen contained within the kerogen (Tissot et al., 1974; Tissot & Welte, 1984; Peter & Cassa, 1994; Dembicki, 2009). The Ogbunike shales have HI values ranging from 26 – 292 mgHC/gTOC (mean = 67 mgHC/gTOC) (Table 2). The laminated, greyish to black shale, have HI that ranges from 77 – 292 mgHC/gTOC suggesting Type II-III mixed oil and gas prone kerogen which correlate with the TOC contents (Figure 7). This interval at the basal part of the quarry represents the most promising in respect to hydrocarbon generation at maturity. The less than 50 mgHC/gTOC are from the bioturbated and sandy shale units. They indicate prevalence of oxidized Type IV inert kerogen from a highly reworked terrestrially derived organic matter.

Table 2. TOC and Rock-Eval data of the shale samples from Ogbunike quarry.

S/N	SAMPLE NO.	TOC	S_1	S_2	Tmax	S_3	HI	OI	PI
1	OB1D	3.94	0.34	3.43	411	1.09	87	27	0.09
2	OB1GB	1.48	0.09	0.40	403	0.69	26	46	0.18
3	OB1GT	1.59	0.10	0.54	401	0.73	34	45	0.16
4	OB2E	3.15	0.29	2.43	409	1.05	77	33	0.11
5	OB2G	0.39	0.05	0.17	408	0.19	42	49	0.24
6	OB2HB	1.45	0.10	0.53	402	0.45	36	31	0.16
7	OB2HT	1.14	0.08	0.38	400	0.47	33	41	0.17
8	OB2RB	2.99	0.27	2.69	420	0.90	89	30	0.09
9	OB2RM	2.64	0.24	3.15	424	0.72	119	27	0.07
10	OB2RT	2.51	0.23	2.95	424	0.93	117	36	0.07
11	OB3DB	1.17	0.04	0.45	406	0.62	38	53	0.08
12	OB3DT	1.09	0.07	0.51	409	0.45	46	41	0.12
13	OB3EB	1.12	0.08	0.40	405	0.63	35	56	0.17

14	OB3ET	1.79	0.10	0.69	406	0.76	38	42	0.13
15	OB3F	1.46	0.07	0.42	410	0.79	28	54	0.14
16	OB3LB	1.31	0.06	0.38	403	0.62	28	46	0.15
17	OB3LT	2.53	0.13	1.08	412	0.98	42	38	0.11
18	OB3O	8.81	1.61	25.74	424	1.64	292	18	0.06
19	OB4B	4.07	0.33	4.34	415	1.29	106	31	0.07
20	OB4E	1.75	0.08	0.58	410	0.86	33	49	0.13

TOC (Wt %), S_1, S_2 (mgHC/g rock), S_3 (mgCO_2/grock), Tmax (°C), HI (mgHc/gTOC), OI, PI

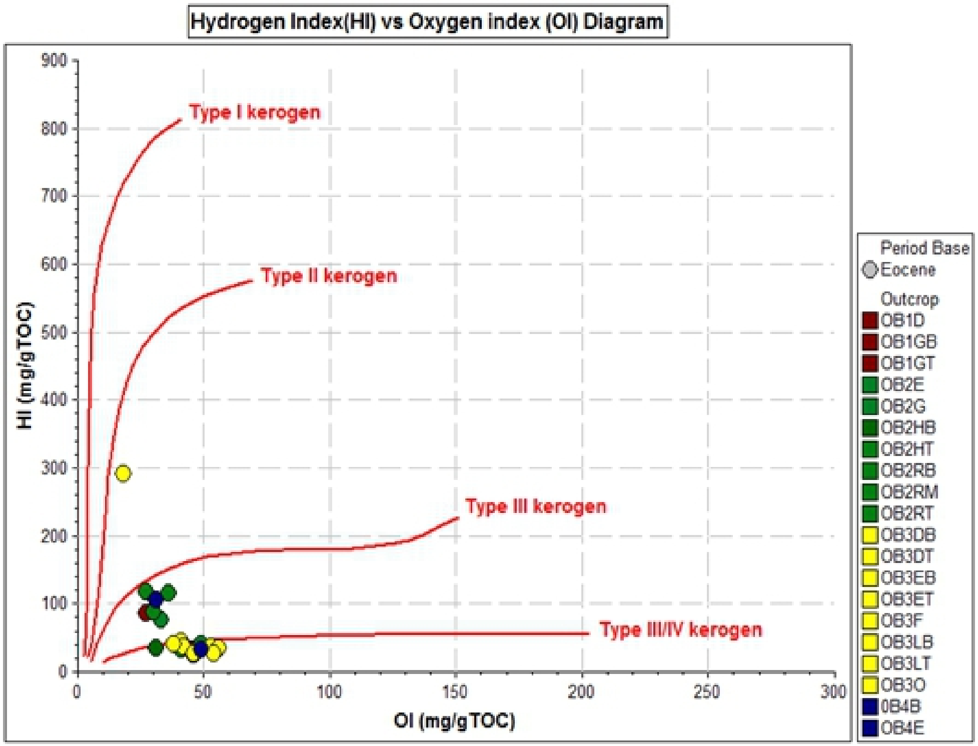

Figure 7. Van Krevelen Hydrogen Index versus Oxygen Index plot of the organic matter from the Bende-Ameki Formation at Ogbunike.

The source potential values for the investigated shales range from 0.22 – 25.74 kgHC/ton of rock (mean of 2.78 kgHC/ton of rock). The value ranging from 0.22 - 1.21 indicates poor hydrocarbon potential, values ranging from 2.72 - 4.67 indicate fair to moderate hydrocarbon potential, and above 5.0 kgHC ton of rock suggest excellent potential for hydrocarbons. It was noted that the 25 cm thick (OB3O) black shale unit have source potential of 27.35 kgC/ton of rock (Table 2, Figure 8) which is consistent with the TOC of 8.81 % and 292 mgHC/gTOC hydrogen index. Thus, this indicates a good source of hydrocarbon generation at maturity. Asides the OB3O units and other laminated black shales unit, all other intervals have very low generative potential.

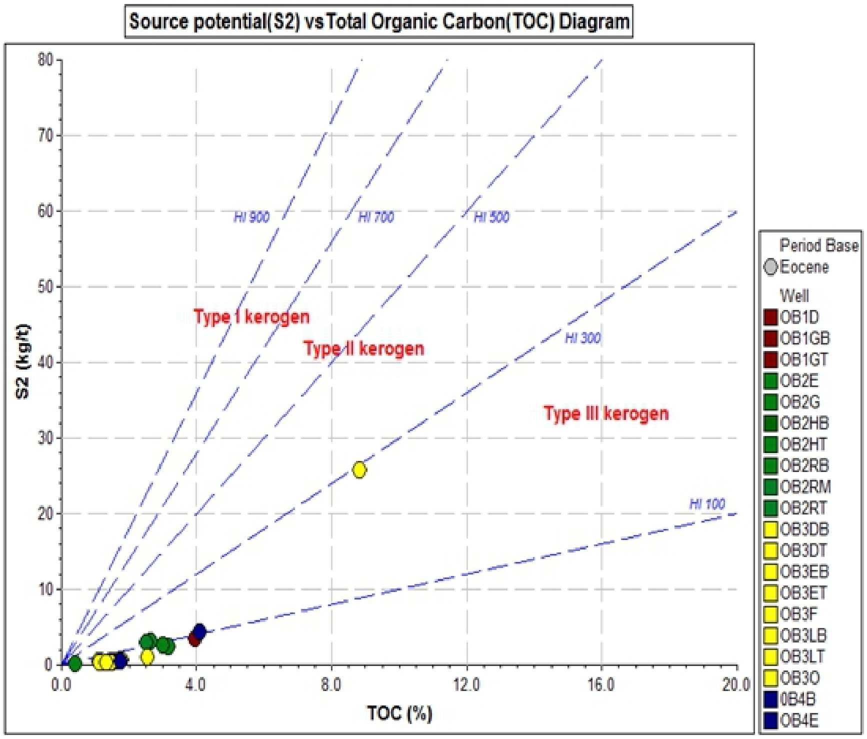

Figure 8. Source Potential (S2 kg/t) versus Total Organic Carbon (TOC wt %) of the studied shales at Ogbunike.

Thermal Maturity

Tmax measures thermal maturity based on the Rock-Eval pyrolysis oven temperature at maximum S_2 generation. T-max is not an equivalent of geologic temperatures attained. It is partly determined by the type of organic matter (Peters, 1986), the temperature gradient in the basin, which is mainly controlled by the basal heat flow through time and burial depth of the sediments and time (Peter & Cassa, 1994). The significance of Tmax with maturation of a source can also be understood by realizing that organic compounds with smaller activation energies generate petroleum faster than organic compound with larger activation energies (Nordeng, 2012). Hence, the maturation level of a kerogen may be estimated from Tmax. Tmax value of the shales in range from 401- 424 ^{o}C, with an average 410 ^{o}C, indicates that they are immature at the current outcrop level (Figure 9).

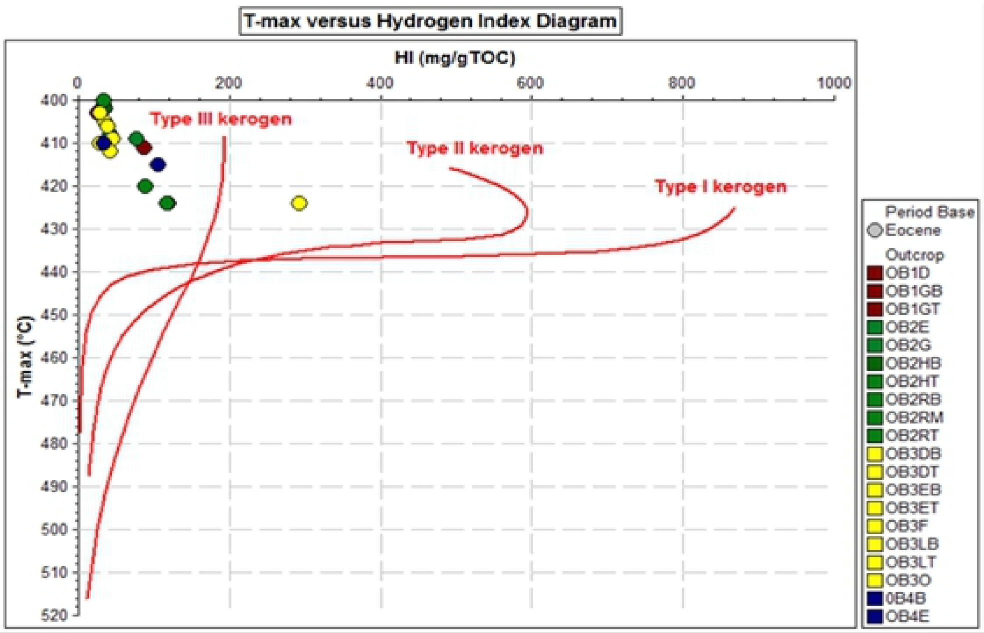

Figure 9. HI against Tmax (^{0}C) diagram for the interpretation of kerogen types and maturity of the Bende-Ameki shales at Ogbunike.

Conclusions

The Ogbunike section consists of shales, claystones, siltstones, and sandstones with a coarsening upward sequence representing lithofacies of the Bende - Ameki formation; an outcropping equivalent of the Niger Delta succession in the subsurface. The sandstones are probably shoreface sands, barrier islands near the coastline.

The shale facies in the quarry are most promising at the base of the section within 2m to 6m. They are grey, dark to black, silty, and laminated with some biofacies representing a lagoonal environment to open shelf facies. They have the highest total organic carbon contents and hydrogen index. They are therefore characterized as good source rock.

However, these source rocks of Eocene Bende - Ameki Formation at Ogbunike are currently immature at the present outcrop level, but they have a fair to moderate potential to generate gaseous hydrocarbons at mature levels in the subsurface.

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