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Technological Properties and Geochemical Evaluation of Maastrichtian Coals from Se Nigeria

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ABSTRACT: *The Maastrichtian Mamu and Nsukka Formations in the Anambra Basin (SE Nigeria) consist of a cyclic succession of coals, carbonaceous shales, silty shales and siltstones interpreted as deltaic deposits. Sub-bituminous coals within these formations are distributed in a north-south trending belt from Enugu-Onyeama to Okaba in the north of the basin. %Rr of 0.44 to 0.59% and T_{max} values between 414 and 432^{o}C indicate that the coals are thermally immature to marginally mature with respect to petroleum generation. Hydrogen Index (HI) values range from 183.09 to 344.53mgHC/gTOC while S_1 + S_2 yields values ranging from 117.02 to 242.04mgHC/g rock, suggesting that the coal have gas and oil-generating potential. The TOC ranges from 17.8 to 77.55%, an indication of an excellent source rock of terrestrially derived organic matter. The ratios of Pr/Ph, Pr/n-C_{17} and Ph/n-C_{18} gave values ranging from 6.0 to 9.6, 6.10 to 73.60 and 0.10 to 3.70 respectively. Maceral analyses showed that the coals are dominated by huminite with lesser amounts of liptinite and inertinite. Despite high liptinite contents in parts of the coals, the n-alkane distribution dominated by n-C_{24} – n-C_{31} $_{and}$ HI versus T_{max} diagram classify the organic matter in the coals as Type III kerogen. The n-alkane distributions dominated by long chain and predominance of OEP values ranging from 2.0 to 6.6 further supports the terrestrial nature of the organic matter. The proximate data indicates average values of 5.4% moisture for Onyeama and 8.0% ash for Okpara while Ezimo and Okaba contain 44.5% volatile matter and 6434.21kcal/kg calorific values respectively. These characteristics therefore make these coals environmental friendly for combustion and liquefaction processes.*

KEYWORDS: *Biomarker, Industrial applications, Isoprenoids, Maastrichtian, Petroleum generation.*

I. INTRODUCTION

The Onyeama (ONYE), Okaba (OKAB), Okpara (OKPA) and Ezimo (EZIM) are some of the thick coal seams that are worked both in open cast and subsurface to supply solid fuel to the Nigerian, Nkalagu, local power generating plants as well as for domestic uses. Traditionally, coal petrographic studies are mainly used for determining coal quality, coking properties and composition, paleodepositional environment, or coal rank (e.g vitrinite %R_r, or VIS fluorescence spectra of liptinite macerals; see [1]). More recently multi-analytical approach to coal petrography analysis uses SEM-EDS, microprobe, Rock-Eval pyrolysis, solvent extract, gas chromatography - mass spectrometry (GC – MS) (e.g biomarkers), hydrous pyrolysis [e.g 2, 1, 3, 4]. The changes in coal during its evolution through the different rank stages can be compared with the evolution of various kerogen types. Coal and kerogen follow the same general trend throughout the evolutionary process [5]. A brief account of the relationship between coal properties and usage has been given by [6, 7, 1].

At the core of any petroleum system is a good quality source rock with TOC > 0.5%, HI > 150 mgHC/gTOC, liptinite content > 15%, T_{max} ≥ 430^{o}C, R_o 0.5-1.2% and biomarker validation [8]. This paper deals with the geochemical characterization of coal samples from the Anambra Basin by using the modern techniques of petroleum geochemistry in order to: (i) assess the quality of its organic matter; (ii) evaluate its thermal evolution; (iii) evaluate its proximate properties; and (iv) highlight its potential as a source rock. The results of this study may stimulate interest in planning for other coal usages as well as conversion of coal to liquid petroleum in the Anambra Basin.

II. REGIONAL GEOLOGIC SETTING

Mid-Santonian deformation in the Benue Trough displaced the major depositional axis westward which led to the formation of the Anambra Basin (Fig. 1). Post deformational sedimentation in the Lower Benue Trough, therefore, constitutes the Anambra Basin. Sedimentation in the Anambra Basin thus commenced with the Campano-Maastrichtian marine and paralic shales of the Enugu and Nkporo formation, overlain by the coal measures of the Mamu Formation (Fig. 2). The fluviodetltaic sandstones of the Ajali and Owelli formations lie on the Mamu Formation and constitute its lateral equivalents in most places. In the Paleocene, the marine shales of the Imo and deltaic Nsukka formations were deposited, overlain by the Akata shale and the Agbada formation that constituted

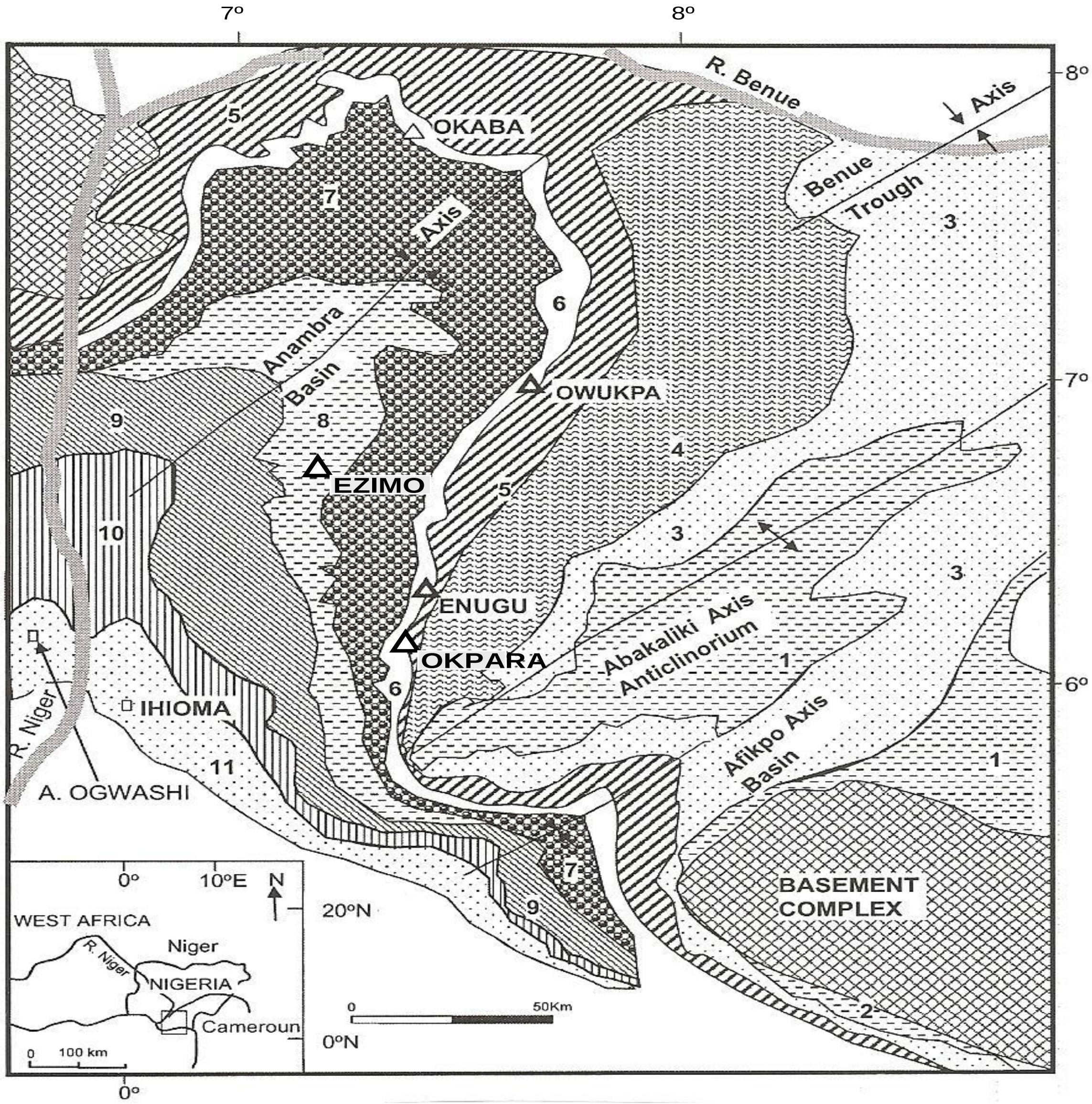


Figure 1: Generalised geological map of the SE Nigeria (boxed areas of inset) showing the location of the coal deposits. Numbers indicate Cretaceous and Tertiary formations 1. Asu River Group; 2. Odikpani Formation; 3. Eze-Aku Shale; 4. Awgu Shale; 5. Enugu/Nkporo Shale; 6. Mamu Formation; 7. Ajali Sandstone;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

the Paleogene equivalents of the Anambra Basin. The best exposure of the Nkporo Shale is at the village of Leru (Lokpauku), 72 km south of Enugu on the Enugu-PortHarcourt express road, while that of Enugu Shale is at Enugu, near the Onitsha-Road Flyover.

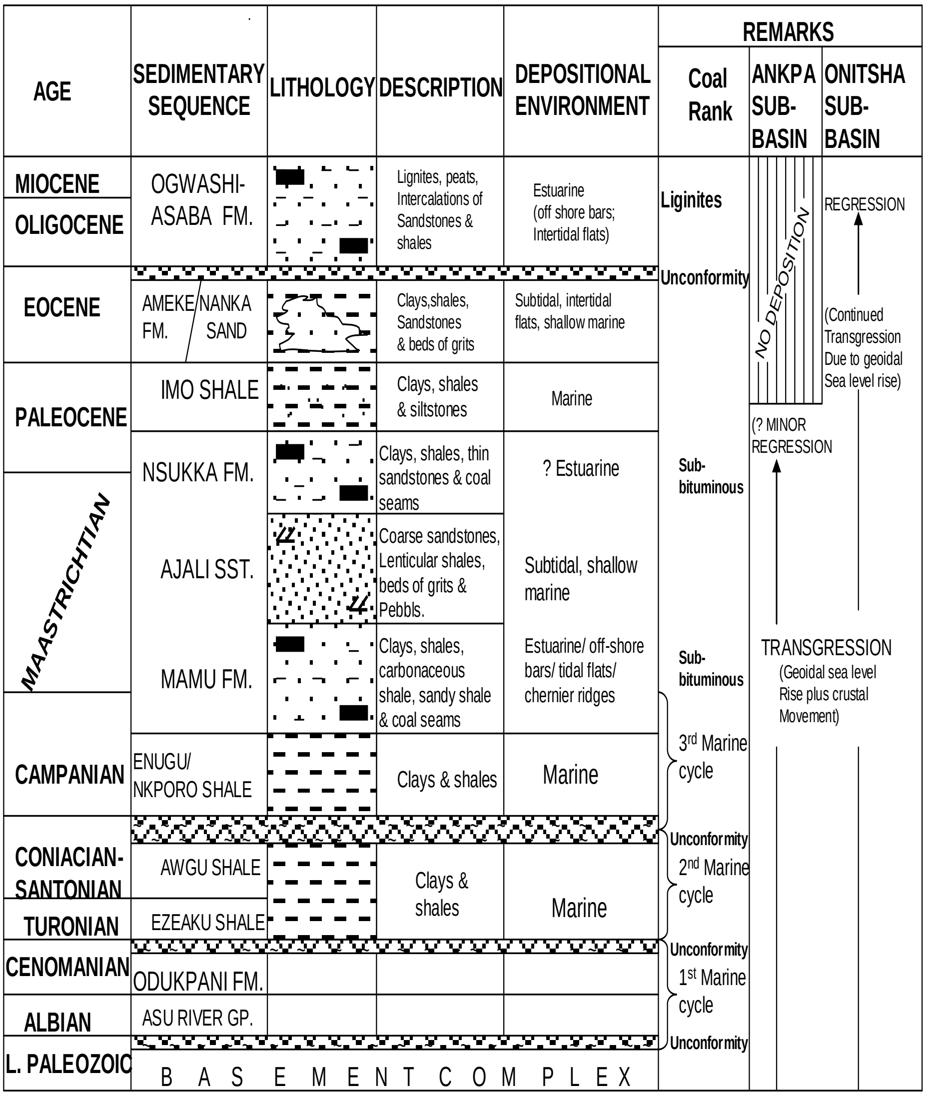


Figure 2: The stratigraphy of the Anambra Basin southeastern Nigeria (modified after [10, 11]).

The Mamu Formation is best exposed at the Miliken Hill in Enugu, with well-preserved sections along the road cuts from King Petrol Station up the Miliken Hills and at the left bank of River Ekulu near the bridge to Onyeama Mine and also at the Onyeama mine. The Nsukka Formation is best exposed at the Iyinzu in Ezimo, with well-preserved section also along the stream channel. Reviews on the geology and stratigraphic successions in the Benue Trough with details on each formation, bed thickness, lateral extensions and stratigraphic locations have been given by [12, 13, 14, 15, 16, 17, 18, 19, 20, 21] amongst others. Details on the evolution and stratigraphic framework of the Anambra Basin have been given by [22, 10, 11, 23, 24]. Details on the stratigraphic successions in the Anambra Basin are depicted on Fig. 2.

III. MATERIALS AND METHODS

Lignites and sub-bituminous coals are widely distributed within the "coal measures" of the Maastrichitian Mamu and Nsukka formations to Miocene Ogwashi-Asaba Formations in the Lower Benue Trough [11]. The coal deposits in the Lower Benue Trough occur mainly in the Enugu province where four mines: Iva valley, Onyeama, Okpara and Ribadu (Fig. 1) are being worked by the Nigerian Coal Corporation. Other coal deposits that are being worked in this area include those at Okaba, Owukpa, Ogboyaga and Ezimo; all found within the Mamu and Nsukka Formations.

A total of 87 coal samples were subjected to laboratory analyses, the samples were reshaped using a rotating steel cutter to eliminate surface that could be affected by alteration. Chips were cut from the samples and dried in an oven at 105^oC for 24 hours. Chips cut perpendicular to bedding were embedded in epoxy and polished following the procedures of [1] to yield polished blocks for reflectance and fluorescence studies using scan electronic microscope. Another portion of the dried sample was pulverized in a rotating disc mill to yield about 50 g of sample for analytical geochemistry. The total organic carbon (TOC) and inorganic carbon (TIC) contents were determined using Leco CS 200 carbon analyzer by combustion of 100 mg of sample up to 1600^oC, with a thermal gradient of 160^oC min^{-1}; the resulting CO_2 was quantified by an Infrared detector.

The sample with known TOC was analyzed using a Rock-Eval 6, yielding parameters commonly used in source rock characterization, flame ionization detection (FID) for hydrocarbons thermal conductivity detection (TCD) for CO_2. One milligram of bulk powder sample was added to 200 mg of KBr and the mixture homogenized using a pestle in an agate mortar. Pressing the mixture using a load of 10 t yielded a pellet for Fourier Transform Infrared (FT-IR) Spectroscopy using a Nicolet Bench 505P Spectrometer, with sample absorbance monitored using 256 scans with resolution of 4 cm^{-1} from a wave-number of 4000 – 400 cm^{-1}. About 10 g of the sample was subjected to sohxlett extraction using a solvent mixture of acetone, chloroform and methanol (47: 30: 23 v/v) at 60^oC for 24 hours to extract the soluble organic matter. The extract was concentrated by evaporation to dryness using a rotating vapour evaporator at 250 mb. The extract was transferred to an 8 ml vial using the same solvent mixture and allowed to evaporate to dryness in a vented hood. The dried extract was fractionated by silica gel column chromatography with a column prepared using 2 g of baker silica gel calcined at 200^oC for 24 hours to yield six fractions ranging from saturate to polar.

The saturate fraction was subjected to urea adduction to separate isoprenoids from *n*-alkanes and subjected to gas chromatography-mass spectrometry (GC-MS) using a CE 5980 GC coupled to an HP Finnigan 8222 MS held at 80^oC for three minutes and raised to 310^oC at 3^oC min^{-1} and held isothermally for 10 minutes in order to assess some molecular parameters used in source rock characterization.

IV. RESULTS

4.1 Organic petrography

The coal samples from the Onyeama, Okpara, Ezimo and Okaba mines in general are dominated by huminite with lesser contents of inertinite and liptinite (TABLE 1). These coals are duroclaritic in nature (Fig. 3). The macerals are not uniformly distributed and their proportions vary within individual seams. Samples from the Onyeama seams contain large amounts of huminite (73.57–89.64 vol.%; mean = 78.81 vol.%), low contents of inertinite (2.61–16.30 vol.%; mean = 9.46 vol.%) and generally low contents of liptinite (5.50–13.81 vol.%; mean = 10.01 vol.%).

Table 1: Huminite Reflectance (%Rr) and Maceral Composition (vol.% m.m.f.) of the Onyeama, Okpara, Ezimo and Okaba Sub-bituminous Coals (nd = Not Determine).

Sample N0.	LOCATION	R_r (%)	H	Ht	Hc	Hd	L	S	C	R	Ld	A	I	F	Sf	Id	Mc	Sc	Sum (vol.% mmf)
ONYE-9	Onyeama	0.57	89.64	4.53	19.41	65.69	5.50	0.32	0.97	3.20	nd	0.30	4.90	2.90	0.60	0.60	0.60	nd	100.00
ONYE-23	..	0.59	84.70	3.99	18.90	61.80	7.30	1.00	1,90	3.30	0.30	0.70	8.00	2.70	2.70	0.70	2.00	nd	100.00
ONYE-29	..	0.59	76.41	9.30	6.64	60.47	13.29	0,66	3.32	7.97	0.66	0.66	10.30	4.65	3.65	1.33	0.66	nd	100.00
ONYE-34	..	0.59	73.57	19.52	6.31	47.75	13.81	1.20	6.00	5.71	0.30	0.60	2.61	4.20	5.11	1.20	1.20	0.90	100.00
ONYE-40	..	0.59	74.29	19.25	10.03	44.51	9.40	1.25	2,82	3.76	0.63	0.94	16.30	5.64	4.39	2.51	1.25	2.51	100.00
ONYE-43	..	0.59	74.25	21.56	13.77	38.93	10.78	0.60	5.39	3,59	0.60	0.60	14,67	5.69	4.19	2.40	1.20	2.50	100.00
OKPA-44	Okpara	0.58	46.69	17.66	15.56	15.46	13.86	5.68	2.52	3.79	0.63	1.26	39.43	1.26	16.40	10.41	3.15	2.21	100.00
OKPA-46	..	0.55	44.73	18.21	12.78	13.74	18.53	0.64	4.47	8.31	1.60	3.51	36.74	9.58	15.02	9.27	1.92	0.96	100.00
OKPA-49	..	0.59	48.67	18.33	13.00	17.33	15.00	1.67	3.33	6.00	1.67	2.33	35.00	15.00	14.00	5.00	1.67	0.67	100.00
EZIM-55	Ezimo	0.48	66.01	3.96	5.94	56.11	11.55	1.32	0.27	3.30	0.66	nd	22.44	8.25	9.24	3.96	nd	0.99	100.00
EZIM-62	..	0.59	66.87	7.97	6.75	52.15	13.19	1.23	7.36	2.07	1.53	nd	19.94	7.98	10.43	1.53	nd	nd	100.00
EZIM-75	..	0.55	67.92	11.00	5.03	51.51	13.61	2.20	5.35	7.23	2.83	nd	14,47	5.35	5.03	2.83	nd	1.26	100.00
EZIM-77	..	0.59	47.50	31.40	nd	16.10	24.90	2.20	6.50	4.30	11.90	nd	27.60	10.10	8.80	8.70	nd	nd	100.00
OKAB-79	Okaba	0.56	29.50	4.00	8.00	17.50	22.00	5.00	9.00	7.00	1.00	nd	48.50	32.50	7.00	8.00	1.00	nd	100.00
OKAB-81	..	0.59	48.30	10.30	2.70	35.30	26.70	9.40	8.30	7.70	1.30	nd	25.00	7.00	8.00	9.30	0.70	nd	100.00
OKAB-87	..	0.53	70.20	2.60	22.30	45.50	4.60	2.00	2.30	nd	0.30	nd	25.20	24.00	0.60	nd	0.60	nd	100.00

Note: H-Huminite; Ht-Humotelinite; Hc-Humocollinite; Hd-Humodetrinite; L-Liptinite; S-Sporinite; C-Cutinite; R-Resinite; A-Alginite; I-Inertinite; Ld-Liptodetrinite; F-Fusinite;Sf –Semifusinite; Id-Inertodertinite; Mc-Macrinite; Sc-Sclerotinite.

The huminite is predominantly composed of detrohuminite (attrinite and densinite) and telohuminite (especially ulminite). The inertinite consists mainly of fusinite, inertodetrinite and sclerotinite, whereas liptinite macerals are mostly sporinite, cutinite, resinite and rarely alginite in decreasing order of abundance (Fig. 3). In the Okpara mine, samples from the seam are dominated by huminite (44.73–48.67 vol.%; mean = 46.70 vol.%), principally detrohuminite. The inertinite content varies from 35.0–39.43 vol.% (mean = 37.06 vol.%), whereas the liptinite content is high (13.86-18.53 vol.%; mean = 15.80 vol.%).

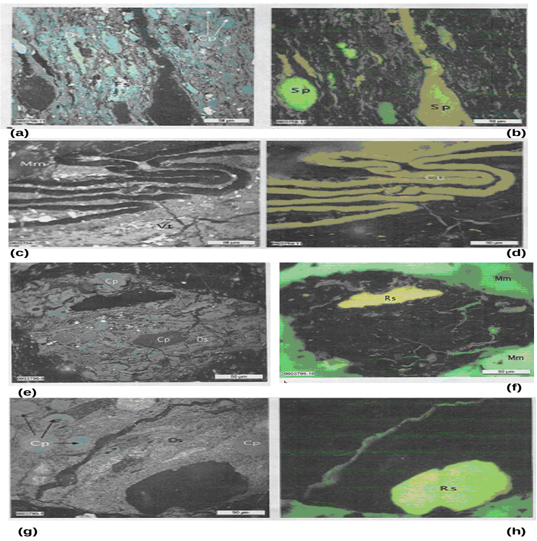


Figure 3: Photomicrographs of samples viewed under white light (left side) and fluorescence light under ultraviolet excitation (right side). (a-b) ONYE-43: Sporinite macerals in a matrix of attrinite and inertodetrinite. Sporinite display orange and brownish fluorescence while inertodetrinite does not fluoresce. (c-d) OKPA-49: Cutinite macerals in a matrix of vitrodetrinite and inertodetinite. Cutinite display brown fluorescence. (e-f) OKAB-81: Resinite macerals associated with corpocollinite in a matrix of vitrodetrinite. Resinite display yellow fluorescence. (g-h) EZIM-75: Same as (e-f) though from different sample field.

The liptinite consists principally of sporinite, resinite, cutinite and liptodetrinite (Fig. 3). Samples from the Ezimo seam show an increasing content of huminite (47.50–67.92 vol.%; mean = 62.08 vol.%). The inertinite content also increases from 14.47–27.60 vol.% (mean = 21.11 vol.%), whereas the liptinite content decreases (11.55– 24.90 vol.%, mean = 15.81 vol.%).

At Okaba, samples from the coal seam have a high content of huminite (70.2 vol.%), principally detrohuminite and gelohuminite (Fig. 3). The inertinite content is quite high (48.5 vol.%), whereas the liptinite content is low (4.6 vol.%). The liptinite is mainly composed of resinite. In samples from the top part of seam, the coal is characterized by varying amounts of huminite (29.5–70.2 vol.%; mean = 49.33 vol.%), a higher content of inertinite (25.0–48.5 vol.%; mean = 32.90 vol.%), and a low to moderate content of liptinite (4.6–26.7 vol.%; mean =17.8 vol.%). Maceral compositions and distributions in coals from the Onyeama and Okaba seams are similar with respect to huminite and inertinite. High contents of huminite occur throughout the seams but increasing contents of inertinite occur towards the Okpara mine. Conversely, high contents of huminite (>90 vol.%) prevail in the part of the Onyeama seam and indeed inertinite contents are generally low (<20 vol.%) throughout these seams. The proportion of liptinite in coals from the four mines varies widely, with the largest concentration (26.70 vol.%) occurring at the Okaba seam. The mineral matter content is generally low in all the studied coal seams, and ranges from less than 1 vol.% to 3 vol.%. Mineral constituents include framboidal pyrite, marcasite, quartz and clay minerals. The Onyeama coals yielded vitrinite reflectance values of 0.57–0.59%Rr; the Okpara coals of 0.55–0.59 %Rr; the Ezimo coals of 0.48–0.55 %Rr (apart from one sample with a reflectance of 0.59 %Rr); and the Okaba coals of 0.53–0.59 %Rr (TABLE 1).

Table 2: Maceral and Vitrinite %Ro Data for Coals from the Anambra Basin Southeastern Nigeria.

Sample Name	Locality	Lithology	Formation	H	L	I	M.M	$\%R_r$
				vol. %				
ONYE	Onyeama	coal	Mamu	79	10	9	2	0.59
OKPA	Okpara	"	Mamu	47	14	36	3	0.57
EZIM	Ezimo	"	Nsukka	62	16	21	1	0.58
OKAB	Okaba	"	Mamu	49	18.5	33	0.5	0.56

4.2 Organic Geochemistry

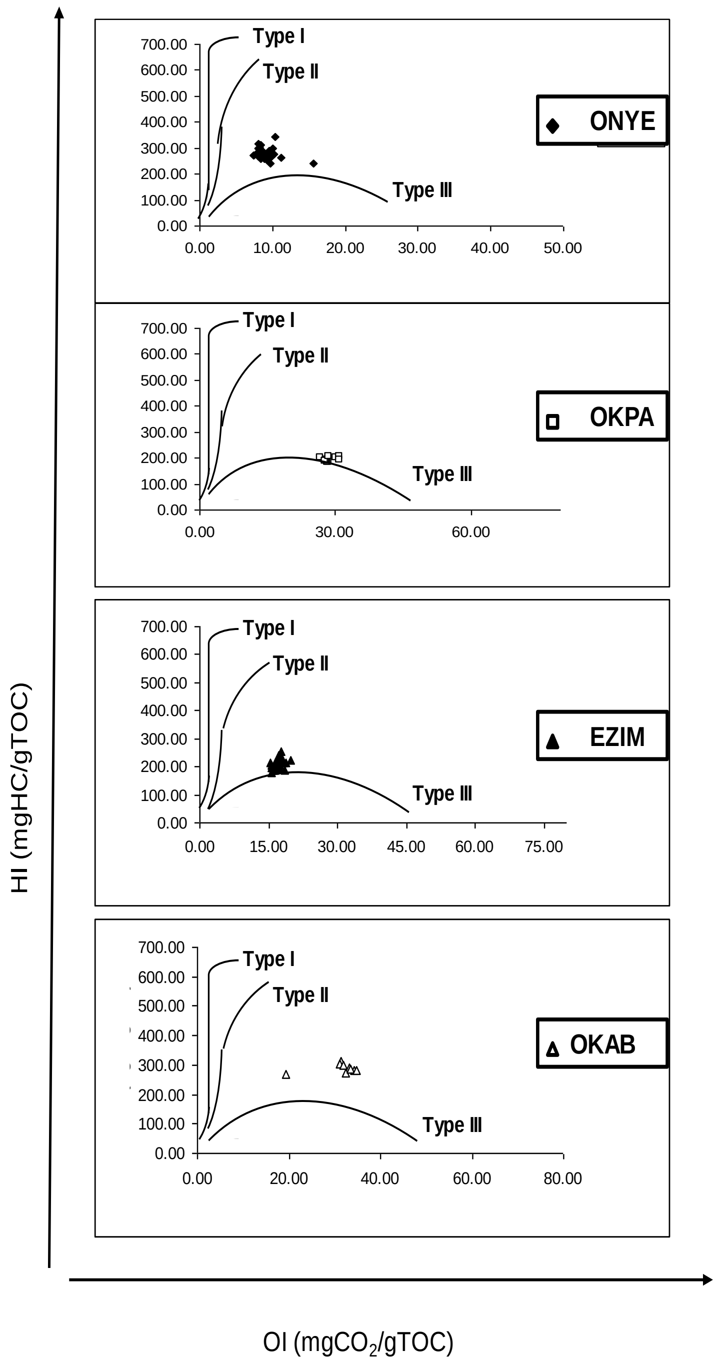
TABLE 3 shows the selected samples for Rock-Eval 6 and organic petrography S_1 ranges from 0.26 in ONYE to 3.52mgHC/g rock in OKAB while S_2 ranges from 124.94 in OKPA to 240.07mgHC/g rock in ONYE. HI ranges from 183.21 in EZIM to 344.50mgS_2/g TOC in ONYE and (S_1+S_2)/g TOC ranges from 126.28 OKPA to 242.04 in ONYE. However, T_{max} value varies from 414^{o}C in the Okaba seam to 432ºC in the Onyeama seam. TOC value consequently varies from 62.35% in the Ezimo seam to 77.80% in the Onyeama seam. S_1 + S_2 and S_2/S_3 value varies from 120.5 mg HC/g rock in the Okpara seam to 242.04 mg HC/g rock in the Onyeama seam and 6.2 in the Okpara seam to 39.2 in the Onyeama seam with mean values of 169.59 and 21.0 respectively. The plot of HI against OI in Figs. 4 determines the kerogen type in the coal samples.

Table 3: Rock-Eval Pyrolysis Data for Samples from Cretaceous Formations from the Anambra Basin.

Sample Name	Sample Type	Locality	FM	Lithology	S1mg/g	S2mg/g	S3mg/g	TOC (%)	TS (%)	T_{max}(°C)	HI mgS2/g TOC	OI mgS3/g TOC
ONYE-1	Mining Pit	Onyeama	Mamu	Coal	1.31	163.06	5.01	61.30	0.56	427	266.00	8.17
ONYE-2	"	"	"	"	1.46	185.45	6.30	71.40	1.17	428	259.73	8.82
ONYE-3	"	"	"	"	1.16	170.01	5.91	61.75	1.02	428	275.32	9.57
ONYE-4	"	"	"	"	1.54	195.20	7.11	76.65	0.84	426	254.66	9.28
ONYE-5	"	"	"	"	1.29	171.01	5.90	63.10	0.86	429	271.01	9.35
ONYE-6	"	"	"	"	1.89	213.73	6.03	75.65	0.95	428	282.52	7.97
ONYE-7	"	"	"	"	1.22	176.97	5.33	66.35	0.69	431	266.72	8.03
ONYE-8	"	"	"	"	1.92	198.69	5.32	72.55	1.04	429	273.87	7.33
ONYE-9	"	"	"	"	0.61	116.41	4.93	44.40	0.74	429	262.18	11.10
ONYE-10	"	"	"	"	2.05	204.58	5.59	75.05	0.58	428	272.59	7.45
ONYE-11	"	"	"	"	1.07	154.58	5.03	55.55	0.90	429	278.27	9.05
ONYE-12	"	"	"	"	1.47	182.93	5.46	63.50	0.94	428	288.08	8.60
ONYE-13	"	"	"	"	1.63	175.90	5.82	63.30	0.60	428	277.88	9.19
ONYE-14	"	"	"	"	1.21	166.98	6.11	60.40	0.90	429	276.46	10.12
ONYE-15	"	"	"	"	1.41	184.53	5.42	65.25	0.98	429	282.80	8.31
ONYE-16	"	"	"	"	1.54	214.42	5.96	77.05	0.93	427	278.29	7.74
ONYE-17	"	"	"	"	1.38	181.77	5.25	64.75	0.88	430	280.73	8.11
ONYE-18	"	"	"	"	1.55	184.50	6.01	71.50	0.91	427	258.04	8.41
ONYE-19	"	"	"	"	1.51	188.80	5.64	54.80	0.88	428	344.53	10.29
ONYE-20	"	"	"	"	1.83	214.00	5.76	72.00	0.80	427	297.22	8.00
ONYE-21	"	"	"	"	1.19	181.16	5.71	65.35	0.78	429	277.21	8.74
ONYE-22	"	"	"	"	1.79	206.26	6.30	74.65	0.82	427	276.30	8.44
ONYE-23	"	"	"	"	0.26	42.78	2.77	17.80	0.47	430	240.34	15.56
ONYE-24	"	"	"	"	1.33	179.84	6.01	64.40	0.90	429	279.25	9.33
ONYE-25	"	"	"	"	0.93	167.09	6.74	69.30	0.88	429	241.11	9.73
ONYE-26	"	"	"	"	1.69	197.16	5.69	68.25	0.72	428	288.88	8.34
ONYE-27	"	"	"	"	1.09	164.37	5.83	60.05	0.97	429	273.72	9.71
ONYE-28	"	"	"	"	1.06	170.09	5.73	60.70	0.87	431	280.21	9.44
ONYE-29	"	"	"	"	1.02	166.63	5.11	62.25	0.69	432	267.68	8.21
ONYE-30	"	"	"	"	1.74	212.60	6.08	74.00	0.92	430	287.30	8.22
ONYE-31	"	"	"	"	1.89	234.34	6.39	77.45	0.40	426	302.57	8.25
ONYE-32	"	"	"	"	1.53	188.25	6.19	65.40	1.11	429	287.84	9.46
ONYE-33	"	"	"	"	1.58	178.35	6.01	59.80	0.56	426	298.24	10.05
ONYE-34	"	"	"	"	1.56	187.32	6.86	69.95	0.69	428	267.79	9.81
ONYE-35	"	"	"	"	1.89	213.76	5.77	68.65	0.67	429	311.38	8.40
ONYE-36	"	"	"	"	1.88	202.66	7.19	77.80	0.68	426	260.49	9.24
ONYE-37	"	"	"	"	1.82	213.48	6.37	75.30	0.52	429	283.51	8.46
ONYE-38	"	"	"	"	1.46	177.29	6.07	62.45	0.69	428	283.89	9.72
ONYE-39	"	"	"	"	2.36	229.25	6.24	76.95	0.47	426	297.92	8.11
ONYE-40	"	"	"	"	2.17	217.96	6.55	77.55	0.67	426	281.06	8.45
ONYE-41	"	"	"	"	2.06	212.27	6.22	74.45	0.76	428	285.12	8.35
ONYE-42	"	"	"	"	2.08	210.29	6.20	72.10	0.72	427	291.66	8.60
ONYE-43	"	"	"	"	1.97	240.07	6.13	76.10	0.73	429	315.47	8.06

Table 3: Continued.

OKPA-44	Mining Pit	Okpara	Mamu	Coal	2.05	128.13	17.05	63.80	0.61	421	200.83	26.72
OKPA-45	"	"	"	"	2.60	134.80	20.21	66.85	0.80	420	201.65	30.23
OKPA-46	"	"	"	"	1.34	124.94	19.39	67.70	0.73	421	184.55	28.64
OKPA-47	"	"	"	"	1.82	118.68	18.30	64.82	0.55	419	183.09	28.23
OKPA-48	"	"	"	"	1.26	132.18	19.13	68.29	0.74	419	193.56	28.01
OKPA-49	"	"	"	"	2.02	137.46	20.58	66.65	0.78	420	206.24	30.88
OKPA-50	"	"	"	"	2.17	126.75	20.42	65.90	0.75	419	192.34	30.99
OKPA-51	"	"	"	"	1.59	120.91	17.89	64.60	0.60	420	187.17	27.69
OKPA-52	"	"	"	"	1.86	128.62	18.03	62.75	0.56	421	204.97	28.73
EZIM-53	Outcrop	Ezimo	Nsukka	Coal	1.39	145.56	11.79	70.20	0.58	425	207.35	16.79
EZIM-54	"	"	"	"	0.81	132.50	13.16	71.20	0.59	426	186.10	18.48
EZIM-55	"	"	"	"	1.72	185.95	12.99	73.05	0.65	420	254.55	17.78
EZIM-56	"	"	"	"	1.03	130.60	11.33	68.00	0.56	424	192.06	16.66
EZIM-57	"	"	"	"	1.75	168.62	12.10	70.50	0.58	423	239.18	17.16
EZIM-58	"	"	"	"	1.41	148.47	10.61	69.35	0.51	425	214.09	15.30
EZIM-59	"	"	"	"	1.25	156.75	13.83	69.80	0.63	423	224.57	19.81
EZIM-60	"	"	"	"	1.37	150.64	13.17	70.40	0.65	425	213.98	18.71
EZIM-61	"	"	"	"	1.39	149.17	11.62	70.35	0.57	422	212.04	16.52
EZIM-62	"	"	"	"	1.18	126.06	10.86	69.95	0.49	424	180.21	15.53
EZIM-63	"	"	"	"	1.25	146.51	12.38	70.80	0.56	423	206.94	17.49
EZIM-64	"	"	"	"	1.23	153.49	13.13	71.75	0.62	421	213.92	18.30
EZIM-65	"	"	"	"	1.15	134.14	11.48	69.25	0.54	426	193.70	16.58
EZIM-66	"	"	"	"	1.38	146.29	11.54	70.60	0.55	424	207.21	16.35
EZIM-67	"	"	"	"	1.58	165.11	12.04	70.30	0.59	423	234.86	17.13
EZIM-68	"	"	"	"	1.36	135.44	11.26	69.20	0.49	425	195.72	16.27
EZIM-69	"	"	"	"	1.31	142.65	11.93	70.80	0.50	424	201.48	16.85
EZIM-70	"	"	"	"	1.20	130.42	11.31	69.15	0.56	425	188.60	16.36
EZIM-71	"	"	"	"	1.27	147.51	11.66	69.35	0.50	425	212.70	16.81
EZIM-72	"	"	"	"	1.47	144.89	11.11	70.95	0.49	425	204.21	15.66
EZIM-73	"	"	"	"	1.15	131.27	11.96	68.05	0.57	426	192.90	17.58
EZIM-74	"	"	"	"	1.33	137.08	11.15	70.40	0.55	425	194.72	15.84
EZIM-75	"	"	"	"	1.33	161.51	12.70	70.55	0.58	423	228.93	18.00
EZIM-76	"	"	"	"	1.07	129.20	11.11	68.85	0.50	425	187.65	16.14
EZIM-77	"	"	"	"	1.30	146.09	11.84	70.70	0.53	426	206.63	16.75
EZIM-78	"	"	"	"	1.07	133.87	10.72	68.20	0.52	427	196.29	15.72
OKAB-79	Mining Pit	Okaba	Mamu	Coal	2.72	196.38	19.69	62.75	0.74	420	312.96	31.38
OKAB-80	"	"	"	"	3.49	182.00	20.73	62.4	0.70	416	291.67	33.22
OKAB-81	"	"	"	"	2.78	173.39	20.61	63.75	0.70	422	271.98	32.33
OKAB-82	"	"	"	"	3.16	172.77	21.20	61.75	0.75	414	279.79	34.33
OKAB-83	"	"	"	"	2.99	195.58	19.90	64.05	0.69	419	305.36	31.07
OKAB-84	"	"	"	"	3.18	170.61	21.51	63.05	0.71	417	270.59	19.24
OKAB-85	"	"	"	"	3.17	188.61	20.04	62.95	0.69	417	299.62	31.83
OKAB-86	"	"	"	"	3.58	180.70	21.04	62.80	0.71	417	287.74	33.50
OKAB-87	"	"	"	"	3.52	178.67	22.05	63.65	0.71	415	280.71	34.64



Figures 4: HI vs. OI plots of coal samples from the Anambra Basin (sample name attached).

Table 4: Triterpanes Indices from GC-MS of the Studied Coal Samples from the Anambra Basin.

Sample Name	Sample Type	Locality	Lithology	Formation	Pr/Ph Ratio	Long/Short Ratio	OEP	Pr/ n-C17	Ph/ n-C18	Ts/ (Ts+Tm)	C_{31}/ $C_{31}+C_{32}$	CPI
ONYE-9	Mining Pit	Onyeama	Coal	Mamu	7.80	30.60	2.20	20.70	2.01	0.01	0.70	1.84
ONYE-23	"	"	"	"	9.60	14.70	2.40	24.50	1.20	0.01	0.72	1.82
ONYE-29	"	"	"	"	7.30	41.90	2.20	13.70	2.60	0.01	0.71	1.80
ONYE-34	"	"	"	"	8.10	25.20	2.20	n.d	2.15	0.01	0.68	1.75
ONYE-40	"	"	"	"	7.60	63.60	2.20	n.d	4.40	0.01	0.71	1.81
ONYE-43	"	"	"	"	8.00	38.90	2.00	n.d	2.70	0.01	0.73	3.64
OKPA-44	Mining Pit	Okpara	Coal	Mamu	8.50	19.00	4.40	17.50	0.80	0.05	0.93	4.49
OKPA-46	"	"	"	"	8.80	40.30	6.80	13.90	0.80	0.10	0.97	6.09
OKPA-49	"	"	"	"	6.00	26.70	5.00	16.00	1.14	0.09	0.94	4.60
EZIM-55	Outcrop	Ezimo	Coal	Nsukka	8.10	41.00	2.80	17.00	0.80	0.08	0.89	5.80
EZIM-62	"	"	"	"	6.90	19.10	3.00	23.20	1.30	0.06	0.87	2.56
EZIM-75	"	"	"	"	6.50	20.70	3.00	n.d	1.50	0.07	0.90	2.61
EZIM-77	"	"	"	"	7.40	16.00	3.00	n.d	1.20	0.06	0.88	2.58
OKAB-79	Mining Pit	Okaba	Coal	Mamu	9.00	3.90	3.70	5.20	0.21	0.04	1.00	2.07
OKAB-81	"	"	"	"	8.40	3.40	2.90	4.00	0.20	0.06	0.98	2.85
OKAB-87	"	"	"	"	8.90	4.20	3.90	4.90	0.20	0.06	0.99	3.43

Fig. 5 shows the chromatogram of the saturate fraction of the coals. The n-alkane distribution is dominated by high molecular weight n-alkane, with maximum at n-C_{29}. Ratios calculated from the chromatogram include a pristane (pr)/phytane (ph) ratio of 7.93 and carbon preference index (CPI) of 3.11 (TABLE 4). Fig. 6 shows the distribution of hopanes investigated at m/z 191 of the non-adduct fraction. The 17αβ-C_{30} hopane is dominant, and a step-like decrease in homohopanes up to C_{34}. The ratio 0.85 of the geo-epimer to the sum of the geo and bio-epimers of homohopane (C_{31} S/S+R) is indicative of equilibrium and support the early maturity of this coal. The common redox proxy (pr/ph) is affected by source organism but its value of 7.93 also indicates major contribution from terrestrial higher plant. Long/Short n-alkanes and Odd over Even Preference (OEP) values varies from 3.4 in the Okaba seam to 63.60 in the Onyeama seam and 2.0 in the Onyeama seam to 6.8 in the Okpara seam with mean values of 25.58 and 3.23 respectively. These further support the high contribution of terrestrial organic matter to the source rock.

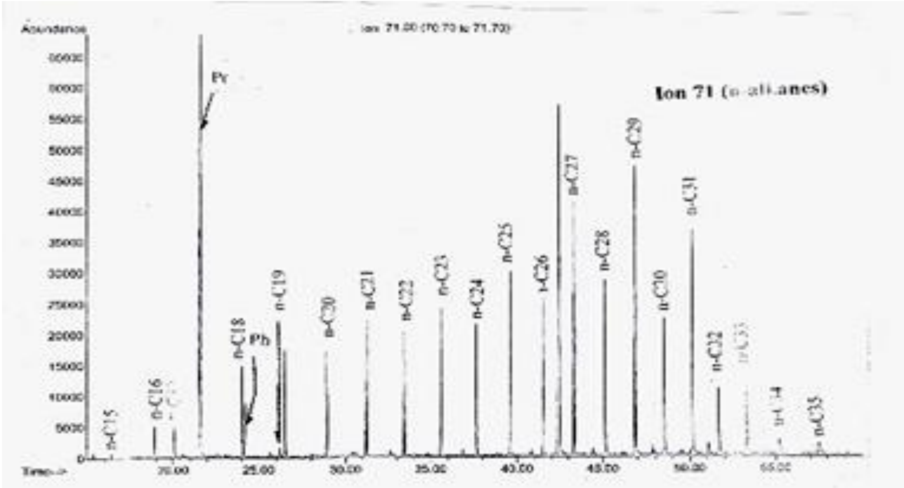


Figure 5: Gas chromatogram of the saturate fraction, with the dominant n-alkane, pristine (pr) and phytane (ph) labeled.

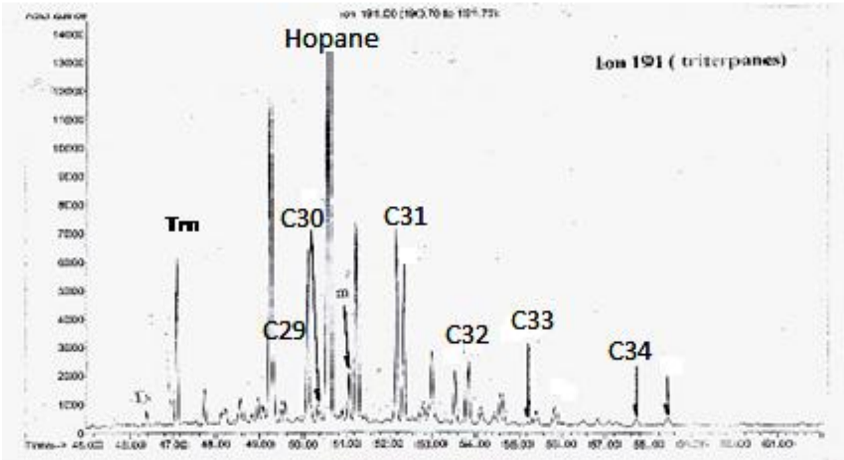


Figure 6: Mass fragmentogram of the non-adduct fraction, showing distribution of hopane at m/z 191.

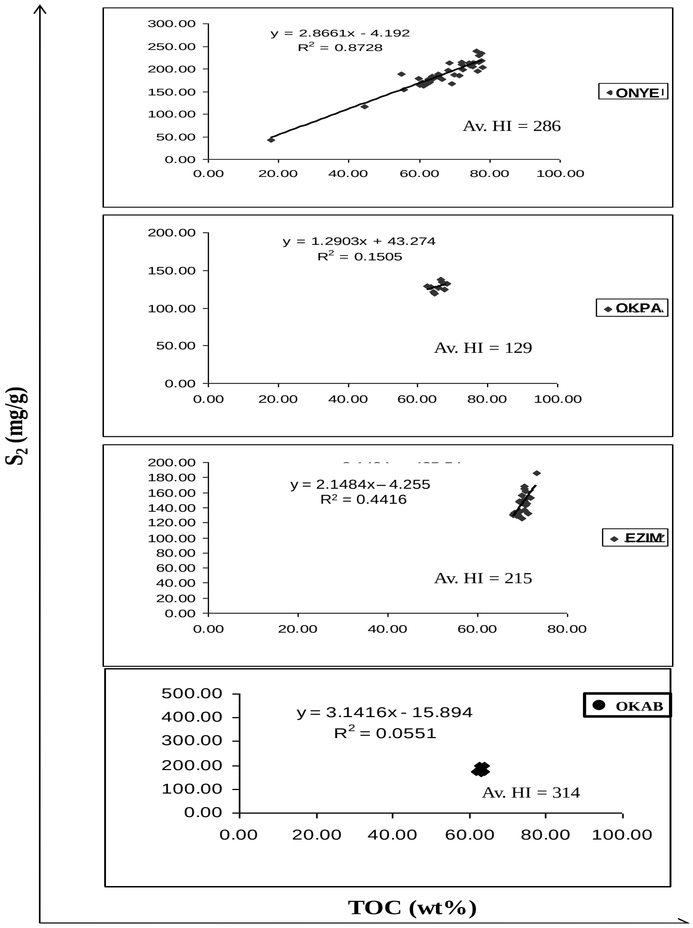
V. DISCUSSION

5.1 Kerogen Types

The average maceral composition (Fig. 3) based on the average percentages of huminite-liptinite inertinite (H: L: I) ratios are: 79:10:9 for the Onyeama coals, 62:16:21 for the Ezimo coals, 47:16:37 for the Okpara coals and 50:18:32 for the Okaba coals (TABLE 2). This indicates a predominance of huminite (Type III kerogen) with contributions of inertinite (Type IV kerogen) and liptinite (Type II kerogen) in the organic matter.

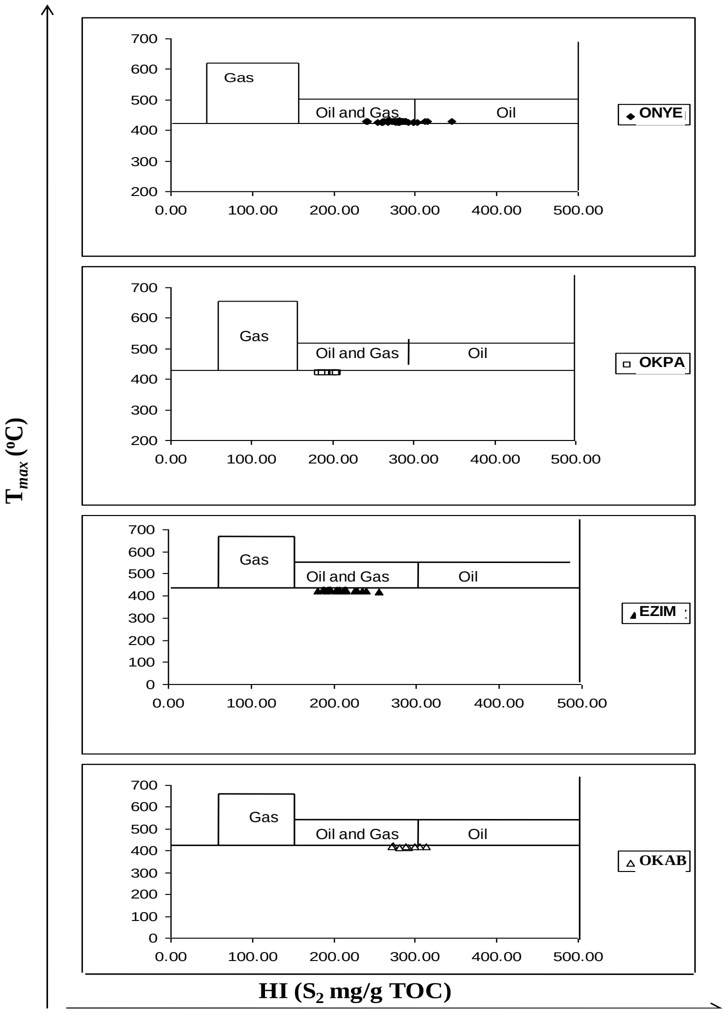
5.2 Rock-Eval 6 Pyrolysis

Rock Eval 6 pyrolysis data are shown in TABLE 3 and plots of the coals as kerogen type are shown in Figs. 4. All of the samples have Hydrogen Indices (HI) on the order expected for oil and gas prone humic coals, although the oxygen indices are lower than expected for normal humic coals. Based on the [25] classification of kerogen in coals relative to HI and OI, all of the samples plot between Types II and III, or within the mixinitic field, where desmocollinite (collodetrinite) is associated with liptinites as a good potential for the generation of oil/gas [26]. This type of coal facies is considered to have enhanced liquid petroleum generative potential [25]; a minimum content of 15-20% liptinite is considered to be the threshold for a coal to be considered as a potential petroleum source rock [27, 2]. Plots on the modified Van Krevelen diagram for samples from the Maastrichtian coals show a mixied range of type II and type III organic matter, with dominance of type II (Figs. 4). However, the location of the highest HI samples could be assigned to a high- potential type III kerogen at the diagenesis/catagenesis boundary [28]. This backed up by the nonoccurrence of notable type I organic matter in the petrographic (maceral) facies (Fig. 3). S_1 values are relatively low for coals of this rank and composition [29]. The cause of these low values is not known but may be due to expulsion or oxidation which can reduce S_1 by up to 50% [e.g. 30].



Figures 7: S_2 vs. TOC plots of coal samples from the Anambra Basin with calculated average hydrogen indices (Av. HI), sample name indicated).

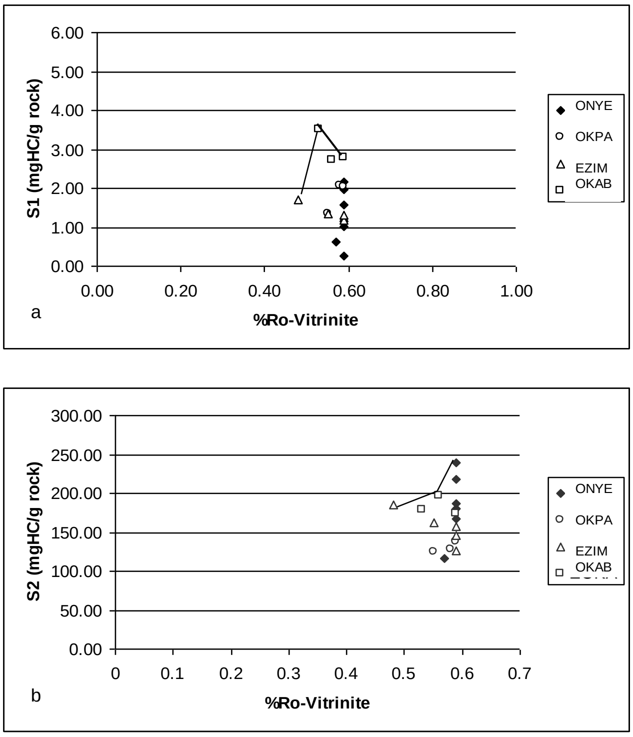
The gas-prone nature of this rock rules out Type II kerogen, which usually shows S_2/S_3 greater than 5, while the maturity from vitrinite reflectance as well as T_{max} suggest that the current HI results from thermal evolution of a Type III kerogen, with initial HI between 600 mgHC g^{-1}TOC and 850 mgHC g^{-1}TOC [31]. High TOC contents (as much as 67.21 wt %) and HI between 183.09 and 344.53 mg HC/g TOC characterize the coal beds of the Mamu and Nsukka Formations. The regression equation based on the S_2 vs. TOC diagrams gave an average HI values of 286, 129, 215 and 314 mg HC/g TOC for Mamu and Nsukka coals (Figs. 7). A plot of S_2 vs. TOC and determining the regression equation has been used by [32] as the best method for determining the true average HI and measuring the adsorption of hydrocarbons by rock matrix. The T_{max} and vittrinite reflectance values obtained on the coals indicate immature to early mature stages (early oil window) for the successions in the Anambra Basin. [33] has suggested that at a thermal maturity equivalent to vitrinite reflectance of 0.6% (T_{max} 435^{o}C), rocks with HI above 300 mg HC/g TOC produce oil, those with HI between 300 and 150 produce oil and gas, those with HI less than 50 are inert. However, [29] are of the opinion that coaly source rocks are sufficiently different from marine and lacustrine source rocks in their organic matter characteristics to warrant separate guidelines for their assessment based on Rock-Eval pyrolysis. Based on the study of some New Zealand coals, they concluded that the rank threshold for oil generation in coals is indicated at T_{max} 420-430^{o}C (R_o 0.55-0.6%) and the threshold for oil expulsion at T_{max} 430-440^{o}C (R_o 0.65-0.85%).
A corresponding plot on the HI-T_{max} diagram based on the values given by Peters (1986) indicates an oil and gas generative potential for some of the samples from the Maastrichtian coals (Fig. 8).



Figures 8: T_{max} vs. HI plots of coal samples from the Anambra Basin (sample name attached).

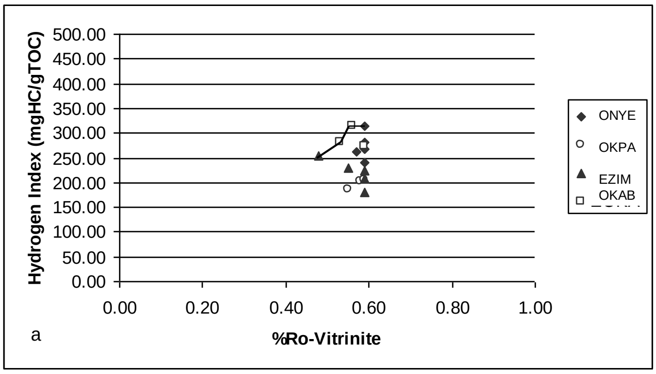
On the selected samples for Rock-Eval 6 and organic petrography S_1 ranges from 0.26 in ONYE to 3.52mgHC/g rock in OKAB while S_2 ranges from 124.94 in OKPA to 240.07mgHC/g rock in ONYE. HI ranges from 180.21 in EZIM to 344.50mgS2/gTOC in ONYE and (S1+S2)/gTOC ranges from 126.28 OKPA to 242.04 in ONYE. Vitrinite reflectance (%R_o) ranges from 0.48 in EZIM to 0.59 in ONYE. These parameters [S_1, S_2, HI and (S_1+S_2)/gTOC] were plotted relative to %R_o (Figs. 9-10).

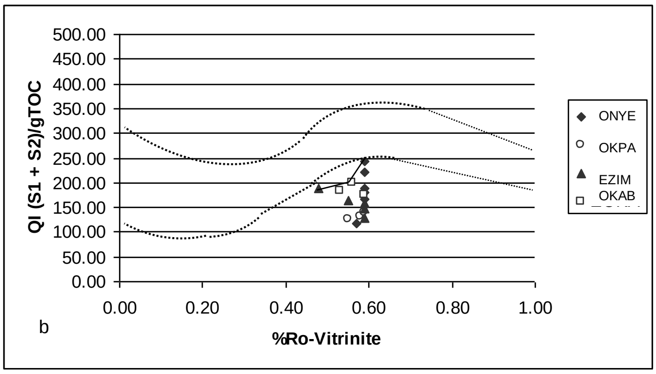
Figs. 9-10 shows the peaks to plateaus exhibited in these plots for S_1, S_2, HI and (S_1 + S_2)/gTOC at 0.58%R_o for HI, and between 0.53, 0.56 and 0.60%R_o for S_1, S_2 and (S_1 + S_2)/gTOC indicating the level of maturity and areas of hydrocarbon generation potential from %R_o. The peaks further shows that areas below %R_o of 0.55 will have low yield of hydrocarbon consequently have low expulsion rate. Larger data sets have been used by [29, 3].



Figures 9: (a) S_1 (mgHC/g rock) versus vitrinite %R_o; (b) S_2 (mgHC/g rock) versus vitrinite %R_o.

Similar peaks in Rock-Eval 6 parameters relative to T_{max} or vitrinite %R_o have been noted previously in coals by [34] (S_1/TOC peak ~1.0%Ro, T_{max} ~450°C), [35] (HI peak at T_{max} ~440°C and ~0.80%R_o), [36] (HI peak at T_{max} ~440°C and ~0.80%R_o), [3] (S_2 and S_1 at 0.85%R_o, HI at 0.90%R_o), and [37] (HI peak ~ 0.90%R_o; between 0.90 and 1.0%R_o for peaks S_2 and S_1+S_2/TOC). The peaks in these coals indicates that hydrocarbon generation potential increases with increasing rank, but further work is required to assess the hydrocarbon potential of the coals from these areas.





Figures 10: (a) Hydrogen Index (S_2/TOC x 100) versus vitrinite %R_o; (b) Quality Index [(mgHC/g TOC; (S_1 +S_2)/TOC x 100] versus vitrinite %R_o. Dashed lines are trend of "hydrocarbon generation" for New Zealand coals from [29] (these authors used the Suggate Index of Coalification instead of %R_o vitrinite).

In agreement with the petrographic composition, the HI versus OI diagram classifies the coals as containing an abundance of Type III kerogen (Figs. 4). Also, atomic H/C ratios of 0.80–0.90 and O/C ratios of 0.11–0.17 show that the coals generally plot in the upper part of the Type III band on a van Krevelen diagram. However, despite the fact that bulk geochemical analyses classify the coals as dominated by Type III kerogen, the petrographic analyses have demonstrated the presence of relatively large amounts of liptinite, such as sporinite and cutinite, in the coals. Although humic coals dominated by huminite have proven to be oil-prone [e.g. 38; 39], the liptinite macerals are more paraffinic in structure and they are likely to be more oil-prone than the huminite. This is favourable for the oil-proneness of the coals, as the oil expulsion efficiency is dependent on the coals' ability to generate long-chain aliphatics (>C_{20-25}) [40].

Gas chromatography and gas chromatography-mass spectrometry analyses of the lipid extracts reported biomarkers with a dominance of long-chain *n*-alkanes (C_{24}-C_{31}) with obvious odd-over-even predominance (Fig. 5). This points to high inputs of terrestrial humic/higher plants organic matter as well as maturity levels below the conventional beginning of oil generation (R_o 0.6%). Pristane/phytane ratios from 6.50 to 9.60 confirm a considerable input of terrestrial organic matter and high levels of aerobic conditions. Fig. 6 shows a low 18α(H)-trisnorneohopanes/17α(H)-trisnorhopanes (T_s/T_m) and relatively high moretanes/17α(H)21β(H)-hopanes (m/αβH) ratios indicate maturity below the conventional beginning of oil generation [41]. With increasing maturity, 17α(H)-trisnorhopanes (T_m) normally transform to 18α(H)-trisnorneohopanes (T_s) and moretanes(m) to 17α(H)21β(H)-hopanes(αβH) [42]. However, the trend observed in this study shows that the Ts is dependent on the lithology and is generally suppressed in the coals compared to shales of the same vitrinite reflectance maturity [28]. 18α(H)-trisnorneohopanes does not appear in the coaly facies until a vitrinite reflectance maturity of about 0.7% (R_o) is attained, whereas in the shales the T_s begins to appear already as early as R_o maturity of about 0.5%.

5.3 Thermal maturity and coal rank

The average T_{max} values of the Onyeama, Okpara, Ezimo and Okaba coals are 428ºC, 420ºC, 424ºC and 418ºC, respectively. This implies that the Onyeama coals are slightly more mature than the coals from the other three localities. Vitrinite reflectance values support this; the average vitrinite reflectance value of the Onyeama coals is 0.59%Rr, whereas the Okpara coals had an average reflectance value of 0.57%Rr while Ezimo and the Okaba coals have an average values of 0.58 and 0.56%Rr respectively. Hopane ratios, however, are consistent with the T_{max} and vitrinite reflectance values, as the Onyeama coals have lower hopane C_{31}S/(S+R) ratios (0.71) than the Okpara, Ezimo and Okaba (0.95, 0.90, 0.99) coals (TABLE 4). The Okpara, Ezimo and Okaba coals are thus thermally immature with regard to petroleum generation, whereas the Onyeama coals are immature to potentially marginally mature. [43] established threshold values for various types of kerogens T_{max} for the beginning of the oil and gas windows. The CPI of 3.11 supports the early maturity indices discussed above, though this parameter is usually high in marine source rocks that produce mostly high molecular weight hydrocarbons [44]. For Type III kerogen, the onset of hydrocarbon generation occurs at a T_{max} value of 435ºC. According to the T_{max}-vitrinite reflectance relationship established for humic coals by [38], this corresponds to ~0.73%Rr. [45, 29, 3, 38] have shown that in humic coals a time-lag exists between the onset of petroleum generation and the onset of efficient oil expulsion at the start of the effective oil window (the "oil expulsion window"). Although petroleum generation in humic coals starts at 0.5–0.6%Rr, the lowest maturity at which efficient expulsion may occur were determined to be around 0.65%Rr for Cenozoic coals [38]. Most coals start to expel at higher maturities. The high content of oil-prone aliphatic kerogen, such as cutinite, in some of the Mamu Formation coals may, however, generate hydrocarbons earlier than the vitrinitic kerogen and may in addition facilitate saturation of hydrocarbons to the expulsion threshold at lower maturities than "pure" humic coals [9].

Table 5: Percentages of m\Moisture, Ash Contents, Volatile Matter and Calorific Values of Coal Samples

Sample Name	Sample Type	Locality	Lithology	Formation	%Moisture Content	%Ash Content wf	%Volatile Matter waf	% Fixed Carbon	Calorific Values (kcal/kg) wf
ONYE-9	Mining Pit	Onyeama	Coal	Mamu	2.98	39.66	47.18	10.18	4433.00
ONYE-23	"	"	"	"	13.98	31.50	45.18	9.34	1679.70
ONYE-29	"	"	"	"	3.15	21.18	43.39	32.28	6067.00
ONYE-34	"	"	"	"	4.00	11.19	44.38	40.43	6853.40
ONYE-40	"	"	"	"	4.15	3.16	45.21	47.48	7557.90
ONYE-43	"	"	"	"	4.11	3.94	47.30	44.65	7621.80
OKPA-44	Mining Pit	Okpara	Coal	Mamu	6.73	11.77	45.58	35.95	6247.60
OKPA-46	"	"	"	"	7.17	4.57	45.80	42.46	6627.00
OKPA-49	"	"	"	"	6.40	7.66	45. 92	40.36	6417.90
EZIM-55	Outcrop	Ezimo	Coal	Nsukka	6.48	3.09	47.90	42.53	7222.00
EZIM-59	"	"	"	"	7.23	4.17	46.09	42.51	7146.20
EZIM-62	"	"	"	"	6.70	9.02	41.39	42.89	6804.60
EZIM-75	"	"	"	"	6.70	6.05	44.92	42.33	7060.30
EZIM-77	"	"	"	"	6.36	8.40	41.98	43.23	6833.70
OKAB-79	Mining Pit	Okaba	Coal	Mamu	6.23	13.25	53.94	26.58	6393.30
OKAB-81	"	"	"	"	6.75	12.09	52.67	28.49	6433.30
OKAB-87	"	"	"	"	7.04	11.48	53.25	28.23	6475.60

5.4 Industrial Application

The low ranks of the coals examined from the Anambra Basin are favourable for easy pulverization, combustibility, a property which provides the ignition temperature point of coals depends on the maceral contents [46]. Decrease in ash contents favors the amount of calorific value thereby giving best quality for combustibility. The moisture content from Onyeama samples range from 1.98 to 4.15% with mean value of 3.40%. Ash content ranges from 3.16 to 39.66 with mean values between 6.10% in Ezimo to 18.40 in Onyeama (TABLES 5).

5.4.1 Combustion

The calorific value ranges from 6067.00 to 7621.80kcal/kg (TABLE 5). Combustibility depends solely on the amount of organic carbon with decrease in ash and moisture contents of a given sample [1]. Generally, Anambra Basin coals contain good combustion quality as its ash and moisture contents are low [26]. On the average, the amount of calorific value obtained from ONYE (7025.03kcal/kg) makes its samples best combustion quality (Fig. 11). [47] is of the opinion that the best combustion property a coal can obtain to produce good quality combustion is by having calorific value ranging from 5500 to 8500kcal/kg under low heteroatoms. [48] reported that for a coal to have good property for industrial applications, its ash content must be less than 20%.

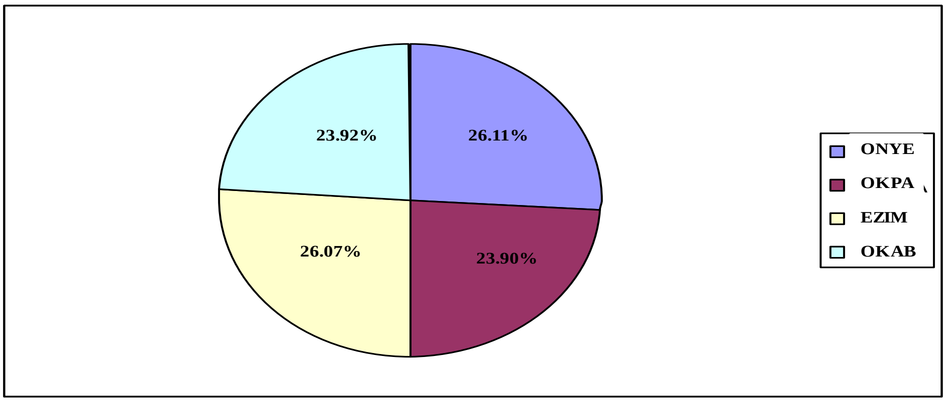


Figure 11: Showing the percentage of Calorific values of coals from four localities in the Anambra Basin by using pie diagram.

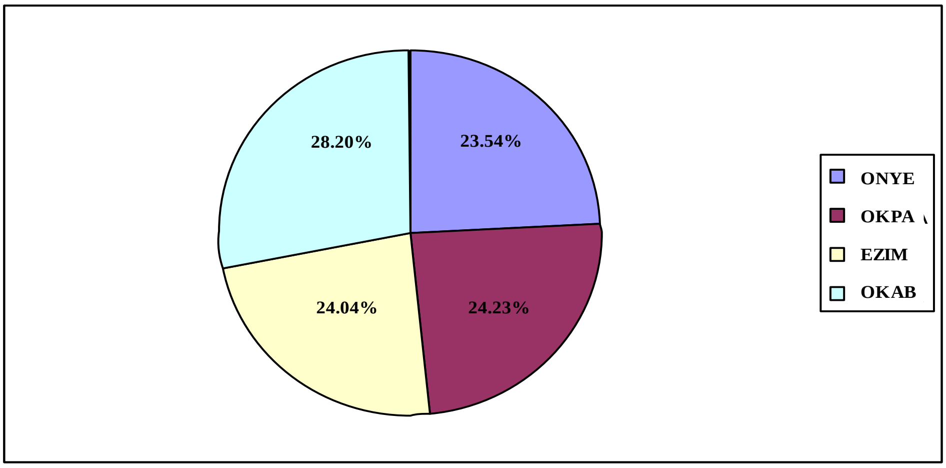


Figure 12: Showing the percentage of Volatile matter of coals from four localities in the Anambra Basin by using pie diagram.

5.4.2 Liquefaction

Volatile matter, apart from its use in coal ranking, is one of the most important parameters used in the coal industry, determining other suitable application of coals as in liquefaction [49]. The value of volatile matter ranges from 43.39 to 53.30% (TABLES 5). With regards to these values, coals from Anambra Basin has appreciable amount of volatile matter content for a qualitative liquefaction. In both analytical and calculated results, Okaba contains the best quality. This is supported by the corresponding diagram (Fig. 11) where OKAB contains the highest volatile matter content. This is supported by the amount of reactive macerals [vitrinite and liptinite (V + L)] of 93.00% obtained by [26].

5.4.3 Carbonization

Previous studies have shown that Anambra basin coals are generally non-coking [50, 51, 52, 53]. The Anambra basin coals have poor coking quality and this is due to their low ranks between high and medium volatile sub-bituminous with R_r of 0.48 to 0.59% obtained by [26]. On the other hand, coal seams from Obi/Lafia area of the Middle Benue Trough occur intercalated within the sediments. These coal seams have $\%R_o$ values ranging from 0.74 to 1.25% and/are regarded as a good quality coke [21]. At the upper Benue trough, sub-bituminous coals from Kumo, Maiganga and Doho are not good in coke making [54].

4.5 Hydrocarbon Generative Potential

The generation potential is highly dependent on the chemical composition of the organic matter input, which suggests an overall vegetational control on the source potential of coals. Such a control may be reflected in coals of different age due to the evolution towards more complex and diversified higher land plants from the Carboniferous to the Cenozoic [39]. [55] suggested that evolution in the peat mire flora may account for a higher oil generation potential of Jurassic and younger coals compared to Palaeozoic coals; for Australian coals, this was attributed to a higher liptinite content in the younger coals. An improved oil generation capacity of Australian coals from the Permian to the Cenozoic has since been supported by [56], who also noted a substantial aliphatic component in vitrinite. Recently, [57] showed that, in particular Mesozoic and Cenozoic coals rich in either liptinite or collodetrinite (formerly named desmocollinite) can be enriched in 'linear aliphatic polymers' and thus possess the high relative concentration of nC_{19}+ hydrocarbons. [58] identified a general trend for Cretaceous – Eocene New Zealand coals whereby coals derived from angiosperm plants had a greater generation potential than coals derived from gymnosperm plants. It therefore, seems likely that an overall floral control can explain why Carboniferous coals are principally related to large gas accumulations, such as in the southern Northern Sea and The Netherlands (e.g., Groningen Field, one of the largest gas fields in the world), whereas Cenozoic coals may be related to significant oil accumulations, particularly in SE Asia [59, 60, 61] and in the Anambra Basin [50, 28]. The varying source potential of coals of different geological age is also reflected in different effective oil it's expelled, with Cenozoic coals both reaching the expulsion threshold at lowest maturity and displaying the broadest effective oil window [38, 39, 62, 63].

VI. CONCLUSION

Coals from the Maastrichtian Mamu and Nsukka Formations in the Anambra Basin, SE Nigeria, are of sub-bituminous rank. With regard to petroleum generation, coals from the Okpara, Ezimo and Okaba mines are thermally immature, whereas coals from Onyeama are thermally immature to marginally mature. The coals are dominated by huminite, and are classified as Type III kerogen both by Rock-Eval and elemental (atomic H/C and O/C) ratios. Coal ranks range from a low of $0.56\%R_o$ at Okaba to a high of $0.59\%R_o$ in the Onyeama area. As well as, T_{max} (°C) values increase with increasing vitrinite $\%R_o$ values. The classification of kerogen in these coal samples relative to HI and OI, of all the samples falls between type II and type III or within the mixinitic field with good potential for the generation of oil/gas. This is confirmed by a significant proportion of long-chain aliphatics in the range $C_{24–31}$ in the coal matrix. Some indicators, such as $\%R_r$ and T_{max} consistently indicate an immature to onset of maturity and early to beginning oil expulsion. If thermally mature, the coals could constitute good gas and oil source rocks, and mature equivalents in the Anambra Basin are important elements of the Cretaceous petroleum system in the basin. They may also represent possible source rocks beneath the Tertiary Niger Delta. With regards to oil generation potential, coals from the major-forming periods indicate that Cenozoic coals produce the highest hydrocarbons making coals from the Anambra basin a high hydrocarbon generation potential.

The overall industrial application standards set by various authors were correlated with the data obtained from coals of the Anambra Basin. The highest amount of volatile matter (53.30%) from Okaba made this locality the best quality for liquefaction processes. While Onyeama with the highest amount of calorific value (7025 kcal/kg) produces the best quality for combustion. None of these coal seams met the required quality for good coke making, but can serve as a suitable blend to high bituminous coals.

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