Asian Journal of
Earth Sciences

ISSN 1819-1886

Academic
Journals Inc.

www.academicjournals.com

Asian Journal of Earth Sciences 4 (3): 157-170, 2011
ISSN 1819-1886 / DOI: 10.3923/ajes.2011.157.170

Source Rock Potential and Thermal Maturity of the Tertiary Lignite Series in the Ogwashi-Asaba Formation, Southern Nigeria

J.E. Ogala
Department of Geology, Delta State University, Abraka, Nigeria

ABSTRACT

The source rock potential and thermal maturation of the Tertiary lignite series within the Ogwashi-Asaba Formation, Southern Nigeria was assessed by Rock-Eval pyrolysis, maceral analysis and vitrinite reflectance measurements. The Total Organic Carbon (TOC), Genetic Potential (GP) and Hydrogen Index (HI) values for the coals ranged from 44.93 to 63.54 wt.%, 104.65 to 248.13 mg HC/g rock and 157 to 402 mg HC/g TOC, respectively. These values indicate that the coals have gas and oil generating potential. Maceral analyses showed that the coals are dominated by huminite with subordinate amount of liptinite and inertinite. HI versus Oxygen Index (OI) diagram and atomic H/C ratios of 1.04-1.55 and O/C ratios of 0.27-0.33 classify the organic matter in the coals as Type II kerogen whereas plots of HI versus T_{max} indicated a mixed Type II-III and Type III kerogen, respectively. Vitrinite reflectance values of 0.24 to 0.36% R_o and T_{max} values between 404 and 425°C suggested that the coals are thermally immature with respect to petroleum generation.

Key words: Thermal maturity, petroleum generation, lignites series, Ogwashi-Asaba formation, southern Nigeria

INTRODUCTION

The Nigerian lignite zone, of mid-Tertiary age, extends from Orlu in the southeast, through Nnewi, in a 16 to 20 km wide belt across the Niger River, to Ogwashi-Uku in Delta State (Okezie and Onuogu, 1985). In the west of River Niger, there are several areas (Obomkpa, Ibusa, Okpanam, Illah, Agbor and Ubiaja) hosting lignite fields, whereas the most important seams east of the Niger are found at Oba and Nnewi (Fig. 1). Nigeria has the largest known lignite deposit in Africa with proven reserves exceeding 300 million tons (Orajaka *et al.*, 1990).

Coal is an important source rock for natural gas and crude oil (Murchison, 1987; Hunt, 1991; Mpanju *et al.*, 1991; Clayton, 1993; Hendrix *et al.*, 1995; Sykes and Snowdon, 2002; Petersen, 2006; Petersen and Nytoft, 2006; Davis *et al.*, 2007). The coal deposits of Nigeria occur in the Benue Trough (Obaje, 2009). The Benue Trough of Nigeria, subdivided into Lower, Middle and Upper regions (Obaje *et al.*, 2004), is a sedimentary basin that extends from the Gulf of Guinea in the south to the Chad Basin in the north in a NE-SW trend (Fig. 1).

Studies of the Nigerian lignite deposits date back to more than 80 years (Wilson, 1924; Du Preez, 1945, 1946; Simpson, 1949, 1954; Da Swardt and Piper, 1957; Chene *et al.*, 1978; Okezie and Onuogu, 1985; Oboh-Ikuenobe *et al.*, 2005; Olobaniyi and Ogala, 2011). Relatively little has been written about the hydrocarbon potential of the Nigerian lignite deposits. Okezie and Onuogu, 1985 presented data from chemical and gas analysis of lignites and showed that the lignite deposits have high calorific values, low sulphur but are generally rich in hydrocarbons,

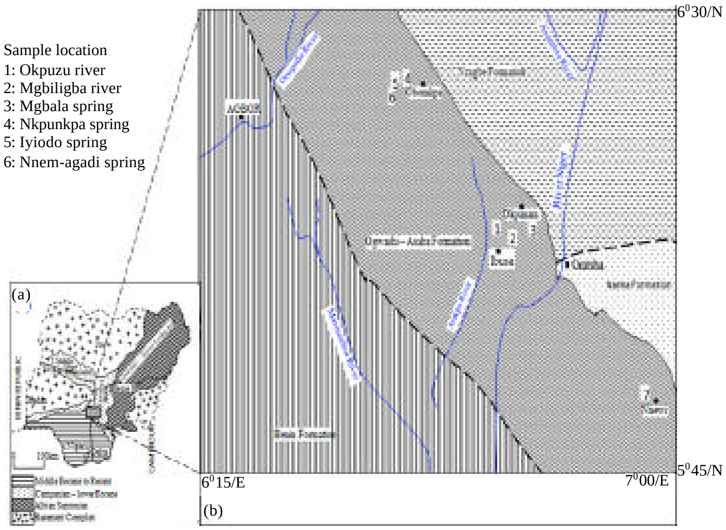

Fig. 1: Geological map showing (a) Southern Nigeria sedimentary Basin and (b) The Ogwashi-Asaba Formation and adjacent units in the study area (modified from Nwajide, 1980)

resins and waxes. Nwadinigwe (1992) studied the wax and resin characteristics of Nigeria's lignites and sub-bituminous coals and concluded that the lower the coal rank the higher the total amount of wax and resin extracted from it. Akande *et al.* (1992) examined the rank, petrographic composition and depositional environment of selected Upper Cretaceous and Tertiary coal of southern Nigeria and concluded that thermal maturation in the Cretaceous successions increases from the post-Santonian (Campanian-Maastrichtian) Anambra Basin into the older Benue Trough where strong diagenetic to anchimetamorphic (that is, very low grade metamorphism) conditions were reached. Obaje and Hamza (2000) investigated the liquid hydrocarbon potential of mid-Cretaceous coals and coal measures in the middle Benue Trough of Nigeria and also subdivided the coal beds into three different coal facies, namely: a vitrinite-fusinite, a trimaceritic and shaly coal facies.

This study attempts to combine organic petrographic studies (maceral analyses and vitrinite reflectance measurements) with organic geochemistry (Rock-Eval II pyrolysis) in order to determine the organic matter content, depositional environment and thermal maturity of the Tertiary lignite series in the Ogwashi-Asaba Formation and thus establish their potential for liquid and gaseous hydrocarbons.

MATERIALS AND METHODS

Geology and stratigraphy of the study area: The present study covers an area of 4,900 km^2 within latitudes 5° 54' to 6° 30' N and longitudes 6° 15' to 7° 00' E (Fig. 1).

The formation of the southern Nigerian sedimentary basin began during the Early Cretaceous (Albian) following the basement subsidence along the Benue and Niger Troughs (Nwachukwu, 1972; Olade, 1975). Folding and uplift occurred in the Santonian along a northeast-southwest trending axis in the Abakaliki-Benue area. The Anambra platform, lying to the west and southwest of the Abakaliki folded belts, subsided to form the Anambra Basin (Reyment, 1965; Short and Stauble, 1967; Murat, 1972; Benkhelil, 1989).

AGE		Formation	Lithlogy	Depositional environment
Quaternary		Benin formation	Sandstones, Clay, Shales	Continental
Tertiary	Plicoene			
	Miocene			
	Oligocene	Ogwashi-asaba formation	Clay, Shales, Sandstones, Lignite	Continental
	Eocoene	Ameki group	Sandstones, Clay, Shales, Limestones	Estuarine, Shallow marine
	Plaeocene	Imo formation	Clay, Shales, Limestones Sandstones, Marl	Shallow marine, deltaic
Upper Cretaceous	Maastrichtian	Nsukka formation	Sandstones, Clay, Shales Coals, Limestones	Fluvio-deltaic
		Ajali formation	Sandstones, Claystones	Fluvio-deltaic
		Mamu formation	Sandstones, Clays, Coals	Shallow marine, deltaic
	Campanian	Enugu/nkporo/owelli formation	Shales, Sandstones, Clay, Ironstones, Siltstones	Shallow marine, deltaic
		Major unconformity		
	Santonian	Awgu formation	Sandstones, Limestones, Clays Coals, Siltstones	Shallow marine, deltaic
	Conician			
Middle cret.	Turonian	Eze-aku formation	Shales, Limestones, Sandstones	Shallow marine
	Cenomanian	Odukpani formation	Sandstones, Limestones, Shales	Shallow marine
Lower Cret.	Albian	Asu river group	Shales, Limestones, Sandstones	Shallow marine
Lower Paaeozoic		Major unconformity		
		Basement complex	Granites, Gneisses, Schists, Migmatites	Igneous, Metamorphic

Fig. 2: Stratigraphic subdivision of southern Benue Trough (modified from Reyment, 1965)

The parahc Ogwashi-Asaba Formation (Oligocene-Miocene) is an important lithostratigraphic unit of the Anambra Basin; it is underline by the regression Ameki formation (Early Econe) and overlain by Miocene-Recent Benin Formation (Fig. 2). The Ogwashi-Asaba Formation consists of a sequence of coarse-grained sandstone, light coloured clays and carbonaceous shale within which are intercalations of lignite seams of continental origin (Kogbe, 1976; Chene *et al.*, 1978). Reyment (1965) suggested an Oligocene-Miocene age for the Ogwashi-Asaba Formation, but palynological study by Chene *et al.* (1978) yielded a Middle Eocene age for the basal part. The lignite seams found within the Ogwashi-Asaba Formation are commonly brownish to black in colour and vary in thickness from few milimeters to a maximum of 6 m. They are thinly laminated and fissile with leaf and woody fragments on fresh cleats.

All the known seams of lignite within the Anambra Basin of Nigeria occur west and east of the Niger (Fig. 1), the thickest seams being located near Ogwashi-Asaba and Obomkpa area in Delta State. These areas have been explored by mapping and drilling. In the Ogwashi-Asaba area, there are two thick lignites, a main seam, averaging 5.2 m in thickness, separated from an upper seam with a mean thickness of 2.4 m by about 3.7 m of clay-shale. The average ratio of overburden to lignite is 6:1, which appears to rule out open-casting (Da Swardt and Piper, 1957). Other lignite zones within the west of the Niger include Ibusa, Okpanam, Illah, Agbor and Ubiaja. The most important seams east of the Niger are found near Oba and Nnewi in Anambra State. At Oba, there is a lower and an upper seam, respectively 2.1 and 0.9 m thick. At Nnewi there are also two seams, the lower one being 3.4 m and the upper 1.2 m thick. Lignites have also been reported near Orlu, Umu-Ezeala and Umuahia in Imo State. The Ogwashi-Asaba lignite outcrops along river valleys, streams/springs in Asaba, Ibusa, Okpanam, Obomkpa and Nnewi (Fig. 1).

Experimental design: A total of seven lignite samples were collected from outcrops at the banks of streams, springs and rivers spread across the Ogwashi-Asaba Formation (Fig. 1). Samples for Total Organic Carbon (TOC) and Programmed Pyrolysis were pulverized and material passing through 250 micron sieve was used for analysis. The samples were treated with concentrated hydrochloric acid to remove carbonates and Total Organic Carbon (TOC) contents of pulverized samples were determined using a LECO 600 carbon analyzer. In Programmed Pyrolysis pulverized samples are heated in an inert environment to measure the yield of three groups of compounds (S_1, S_2 and S_3), measured as three peaks on a program using a Delsi Rock-Eval II analytical equipment (Table 1). The parameters obtained from the Rock-Eval instrument include: total organic carbon (TOC, wt.%), S_1 (free oil content, mg HC/g rock), S_2 (remaining hydrocarbon potential, mg HC/g rock), S_3 (organic carbon dioxide, mgCO$_2$/g rock), T max (temperature at maximum evolution of S2 hydrocarbons, °C), hydrogen index (HI = S_2×100/TOC, mg HC/g TOC), oxygen index (OI = S_3×100/TOC, mg CO$_2$/g TOC), production index (PI = S_1/S_1+S_2), S_2/S_3 and normalized oil content (S_1/TOC, mg HC/g TOC). The TOC and Programmed Pyrolysis analyses were performed at Weatherford laboratories, Texas, USA.

Proximate analysis was performed on the samples according to ASTM standard procedures (ASTM D3174, 2004; ASTM D3175, 2004; ASTM D3302, 2004). Ultimate analysis was carried out according to ASTM D5373, 2004) using a CARLO ERBA Automatic Analyser (Eager 200) calibrated against the CP1 standard reference material. Gross calorific value (Table 2) was determined using an IKA C4000 adiabatic bomb calorimeter (ASTM D5865, 2004).

Polished blocks were prepared from crushed coal according to International Standards (ISO 7404-2, 2004). Maceral analysis was performed in oil immersion using a LEICA DMRX coal-petrography microscope under both white incident light and blue-light excitation (ICCP, 1971, 2001; Sykorova *et al.*, 2005). More than 500 points were determined on each polished block using a SWIFT PRIOR point counter (Table 3). Huminite reflectance was measured on eu-ulminite B (ISO 7404-5, 2004). The organic petrographic studies (maceral analyses and vitrinite reflectance measurements) and elemental analysis were performed by the Department of Geology, University of Patras, Greece.

Table 1: TOC and Rock-eval pyrolysis results

Sampling location	TOC (wt%)	S_1 (mg HC/g rock)	S_2 (mg HC/g rock)	S_3 (mg CO$_2$/g rock)	T max. (°C)	GP (S_1+S_2)	HI (mg HC/g TOC)	OI (mg CO$_2$/g TOC)	S_2/S_3	SI/TO *100	PI (S_1/S_1+S_2rock)
River okpuzu	61.79	2.83	134.0	7.73	415	136.83	217	13	17	5	0.02
Mgbiligba River	60.20	6.13	242.0	8.91	417	248.13	402	15	27	10	0.02
Mgbala spring	63.31	5.15	99.5	8.74	404	104.65	157	14	11	8	0.05
Nkpunkpa spring	63.54	3.11	159.6	8.62	414	162.71	251	14	19	5	0.02
Iyiodo spring	44.93	3.21	134.4	7.33	422	137.61	299	16	18	7	0.02
Nnem-agadi spring	50.25	3.05	172.7	8.38	425	175.75	344	17	21	6	0.02
Ekete spring	57.42	2.04	129.0	8.86	415	131.04	225	15	15	4	0.02

Table 2: Moisture and ash contents of lignite samples from Ogwashi-Asaba Formation (bdl, below detection limit)

Sample location	River okpuzu	Mgbiligba river	Mgbala spring	Nkpunkpa spring	Iyiodo spring	Nnem-agadi Spring	Eketespring
Moisture (wt.%)	37.2	38	39	43.2	35.3	22.2	43.6
Ash (wt.%, d.b.)	05.2	5.6	8	4.1	22.8	69.4	8.4
Volatile matter (wt.%,d.a.f.)	56.2	55.7	59.9	55.9	62.5	70.3	54.9
Fixed carbon (wt.%, d.a.f.)	43.8	44.3	40.1	44.1	37.5	29.7	45.1
C (wt.%, d.a.f.)	66.9	64.3	67	67	66.5	61.3	63.7
H (wt.%, d.a.f.)	5.8	6.5	6.5	8.6	06.4	7.8	7.7
N (wt.%, d.a.f.)	1.0	1.1	1.0	0.4	1.3	1.2	0.9
S (wt.%, daf)	bdl	4.3	bdl	bdl	bdl	7.7	bdl
O^a (wt.%, d.a.f.)	26.3	23.7	25.6	24	25.8	22.1	27.8
H/C^b	1.04	1.22	1.16	1.55	1.15	1.53	1.44
O/C^b	0.29	0.28	0.29	0.27	0.29	0.27	0.33
N/C^b	0.015	0.017	0.015	0.006	0.020	0.020	0.014
S/C^b	-	0.667	-	-	-	0.126	-
Calorific value (MJ kg^{-1}, m.a.f.)	17.1	16.5	16.9	14.6	17.0	20.7	13.8

db: dry basis, daf: dry, ash free, maf: moist, ash-free, ^{a}: calculated after subtraction, ^{b}: atomic ratio

RESULTS

TOC and Rock-eval pyrolysis results: The TOC content of the coals range from 44.93 to 63.54 wt.%, averaging 57.35 wt.% (Table 1). S_1 yields range from 2.04 to 6.13 mg HC/g rock, while S_2 and S_3 yields range from 99.5 to 242.0 mg HC/g rock and 7.33 to 8.91 mg CO_2/g rock, respectively. The Hydrogen Index (HI) values range from 157 to 402 mg HC/g TOC (averaging 270.7 mg HC/g TOC). All the samples have Production Index (PI) value of 0.02 except the sample from Mgbala Spring with production index of 0.05. T_{max} values range from 404 to 425°C (Table 1).

Elemental composition: The moisture contents of the lignite samples range from 35.3 to 43.6%, while that of Mgbala Spring is 22.2% (Table 2). The dry ash contents of the lignite ranges from 4.1 to 22.8% whereas that of sample 6 is 69.4%. The volatile matter content of the lignite varies from 54.9 to 62.5% (d.a.f.) and sample 6 is 70.3% (d.a.f.). Fixed carbon content varies from 37.5 to 45.1% (d.a.f.) while that for sample 6 is 29.7% (d.a.f.). The carbon and hydrogen contents range between 63.7 to 67.0% (d.a.f.) and 5.8 to 8.6% (d.a.f.), respectively. Sample 6 had a lower carbon content of 61.3% (d.a.f.). Nitrogen content varies between 0.4 to 1.3% (d.a.f.). Elemental S is low for all the samples except Mgbiligba and Nnem-Agadi (4.3 and 7.7%, d.a.f.), respectively (Table 2). The oxygen contents range from 22.1 to 27.8% (d.a.f.). The calculated atomic H/C, O/C and N/C ratios vary from 1.04 to 1.55, 0.27 to 0.33 and 0.006 to 0.02, respectively (Table 2). The calorific values range from 13.8 to 17.1 MJ kg^{-1} (m.a.f.) while that of sample 6 is 20.7 MJ kg^{-1} (m.a.f.).

Organic petrography: The lignites samples from Okpuzu, Mgbiligba, Mgbala, Nkpunkpa, Iyiodo and Ekete seams in general are dominated by huminite with subordinate amounts of liptinite and inertinite (Table 3). Ternary plot of the three maceral groups showed that the lignites are mainly of duroclaritic composition except the Nnem-Agadi sample (Fig. 3). The sample from Nnem-Agadi spring is carbonaceous shale and its petrographic features resemble dispersed organic matter.

Table 3: Maceral composition of the studied samples in volume percent, on mineral-matter free basis

Maceral/Mineral	River okpuzu	Mgbiligba river	Mgbala spring	Nkpunkpa spring	Iyiodo spring	Nnem-agadi River	Eketespring
Textinite		1.8	2.6	2.6	3.1	2.4	2.1
Ulminite	10.1	8.4	5.8	21.7	9.1		37.9
Telohuminite	10.1	10.2	8.4	24.3	12.2	2.4	40.0
Attrinite	29.7	7.3	36.3	15.4	27.6	6.0	13.4
Densinite	23.4	50.5	7.2	37.5	8.8		24.9
Detrohuminite	53.1	57.8	43.5	52.9	36.4	6.0	38.3
Levigelinite	1.5	1.4	2.0	2.4	1.2	1.2	0.6
Porigelinite	0.2	0.2	0.4	1.7	0.8		2.0
Corpohuminite	0.6	2.4	0.8	1.3	2.5		3.3
Gelohuminite	2.3	4.0	3.2	5.4	4.5	1.2	5.9
Huminite	65.5	72.0	55.1	82.6	53.1	9.5	84.2
Semifnsinite	0.4		0.4	0.2	0.2		0.6
Macrinite	0.2						
Funginite	1.5	1.4	2.2	1.3	2.3	3.6	1.4
Inertodetrinite	0.8		0.2	1.1	0.4		0.4
Inertinite	2.9	1.4	2.8	2.6	2.9	3.6	2.4
Sporinite	4.2	2.4	4.2	1.7	4.1	11.9	0.2
Cutinite	4.0	2.5	3.4	0.5	7.8	1.2	1.0
Resinite	1.7	1.4	5.6	0.6	5.4		1.0
Alginite	1.3	1.0	1.8	0.4	2.5	17.9	0.4
Suberinite	0.8	1.0	0.4	0.6	0.8		1.4
Bituminite	7.8	9.2	9.5	6.0	11.9	17.9	3.7
Liptodetrinite	11.8	9.1	17.2	5.0	11.5	8.3	5.7
Fluorescing groundmass*					29.8		
Liptinite	31.6	26.6	42.1	14.8	44.0	42.9	13.4
Total organic matter	100	100	100	100	100	100	100
Clay minerals	0.8	0.2	2.7	0.6	3.3	13.2	4.8
Carbonates		0.2			0.2		
Quartz			0.4	0.5	0.2	2.1	0.4
Pyrite		3.7	0.2	1.1	0.9	6.3	4.6
Oxides		0.2	0.2				
Mineral groundmass**						19.4	
Other		0.6	0.4		0.6	0.6	
Mineral Matter***	0.8	4.9	3.9	2.2	5.2	22.2	9.8

*Organic-rich mineral groundmass. **Groundmass consisting of minerals and mollusk shell fragments. ***Volume percent (%) on whole sample basis

Table 4: Huminite reflectance ($Rr_{oil}\%^1$) of lignite samples from Ogwashi-asaba formation

Sample location	R mean	R min.	R max.	Standard deviation	No. of measurements
River okpuzu	0.24	0.20	0.33	0.03	54
Mgbiligba river	0.30	0.23	0.38	0.03	83
Mgbala spring	0.30	0.24	0.33	0.03	75
Nkpunkpa spring	0.31	0.24	0.42	0.03	100
Iyiodo spring	0.32	0.24	0.38	0.03	86
Nnem-agadi river	0.36	0.21	0.48	0.06	45
Ekete spring	0.29	0.23	0.40	0.04	89

[1]: Measured on eu-ulminite B

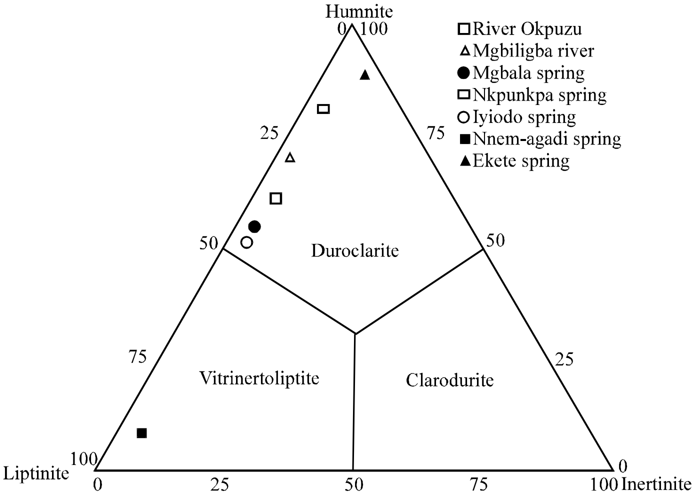

Fig. 3: Ternary plot of the three maceral group showing the duroclaritic and vitinertoliptic composition of the lignites in the Ogwashi-Asaba Formation (Akande *et al.*, 2007)

Samples from Okpuzu, Mgbiligba, Mgbala, Nkpunkpa, Iyiodo and Ekete seams contain large amounts of huminite (53.1-84.2 vol.%; mean = 68.75 vol.%), followed by liptinite (13.4-44.0 vol.%; mean = 28.75 vol.%) and generally low contents of inertinite (1.4-2.9 vol.%; mean = 2.5 vol.%). The huminite is predominantly composed of detrohuminite (38.3-57.8 vol.%). Attrinite is dominant in samples from Okpuzu, Mgbala and Iyiodo seams and densinite in the rest (Table 3), The sample from Ekete seam contain similar amounts of detrohuminite (38.3 vol.%) and telohuminite (40.0 vol.%) due to xylite inclusions (Table 3). Gelohuminite occurs in all the lignite samples at low frequency (1.2-5.9 vol.%). The liptinite content varies from 13.4 to 44 vol.% and consists principally of liptodetrinite (5-17.2 vol.%), bituminite (3-11.9 vol.%), cutinite (0.5-7.8 vol.%), sporinite (0.2-4.2 vol.%), resinite (0.6-5.4 vol.%), alginite (0.4-2.5 vol.%) and suberinite (0.6-1.4 vol.%) in decreasing order of abundance. The sample from Nnem-Agadi is rich in liptinite (86.9 vol.%), mostly composed of alginite (17.9 vol.%), bituminite (17.9 vol.%), sporinite (11.9 vol.%), liptodetrinite (8.3 vol.%) and cutinite (1.2 vol.%) and fluorescing groundmass composed of both minerals and organic matter (29.8 vol.%).

The inertinite content in all the samples is generally low (1.4-3.6 vol.%). The inertinite consists mainly of fuginite, inertodetrinite, semifusinite and macrinite (Table 3).

The mineral matter content is generally low in all the studied lignite seams (0.8 to 9.8 vol.%), mostly comprising clay minerals, pyrite, quartz, oxides and carbonates (Table 3). Nnem-Agadi seam contains a high mineral matter content (41.7 vol.%), fragments of mollusk shells with groundmass consisting of unidentifiable minerals.

The vitrinite reflectance measurements were carried out on eu-ulminite B (Table 4). Random reflectance values obtained for all the lignite samples range from 0.24 to 0.32%R_r (apart from Nnem-Agadi sample with vitrinite reflectance of 0.36%R_r).

DISCUSSION

Quantity and types of organic matter: The geochemical parameters derived from the TOC and Rock-Eval analyses of the lignites are listed in Table 1. Adequate amount of organic matter is required for a source rock to generate oil or gas (Tissot and Welte, 1984). The seven lignite samples

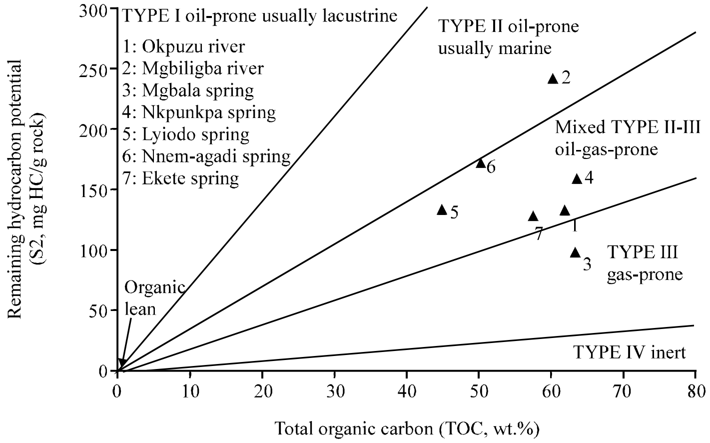

Fig. 4: Plot of remaining hydrocarbon potential (S_2) versus TOC (after Langford and Blanc-Valleron, 1990)

have high TOC contents. The total sulphur contents are low except Mgbiligba and Nnem-Agadl (Table 2). The TOC contents vary from 44.93 to 63.54 wt.%. These values exceed the minimal 0.5 wt.% required for a potential source rock to generate hydrocarbons. The source rock quality of the lignites is confirmed by the pyrolysis-derived genetic potential (G.P. = S_1+S_2). The hydrocarbon generative potential of the lignite samples range from 104.65 to 248.13 mg HC/g rock, suggesting that the samples have great potential to generate hydrocarbons (Tissot and Welte, 1984; Peters and Cassa, 1994). Both S_2 yields and Hydrogen Index (HI) values for the lignite samples are high (Table 1). The high HI (157- 402 mg HC/g TOC) and low oxygen index (OI = 13 -17 mg CO_2/g TOC) supports the high hydrocarbon potential of the lignites. Hunt (1991) and Petersen and Nytoft (2006) have shown that the higher the hydrogen contents of a coal, the greater the ability to generate oil and gas. Hunt (1991) observed that coals can form appreciable amount of oil when the hydrogen content relative to carbon is very high while it will form mainly gas when the hydrogen is low.

The type of organic matter in the lignite samples was assessed by Rock-Eval pyrolysis and maceral composition (Table 1 and 3). The HI values and S_2 yields for the studied lignite samples indicate a moderately good source rock with gas and oil generating potential (G.P.>2 mg HC/g rock; Tissot and Welte, 1984; Peters and Cassa, 1994). The plots of S_2 versus TOC (Fig. 4) are useful in evaluating the petroleum-generative potential of source rocks (Langford and Blanc-Valleron, 1990; Peters, 1986). The slopes of lines radiating from the origin in Fig. 5 is directly related to hydrogen index (HI = $S_2 \times 100/\text{TOC}$, mg HC/g TOC). HI values >600, 300-600, 200-300, 50-200 and <50 mg HC/g TOC classifies organic matter as Type I (very oil prone), Type II (oil prone), Type III (gas prone) and Type IV (inert), respectively (Peters, 1986). The plots of HI versus OI (Fig. 5) classifies the lignites as containing mainly Type II organic matter while HI versus T_{max} (Fig. 6) reveals kerogen of Type II-III organic matter, respectively.

The maceral composition (Table 3) for the lignite samples based on the average percentage of huminite-liptinite-inertinite (H: L: I) ratios are 69:29:2, indicating a predominance of huminite (Type III kerogen) with contributions from liptinite (Type II kerogen) and inertinite (Type IV kerogen) in the organic matter. This result is in agreement with the data obtained by Akande *et al.* (2007). However, the sample from Nnem-Agadi seam have huminite-liptinite-

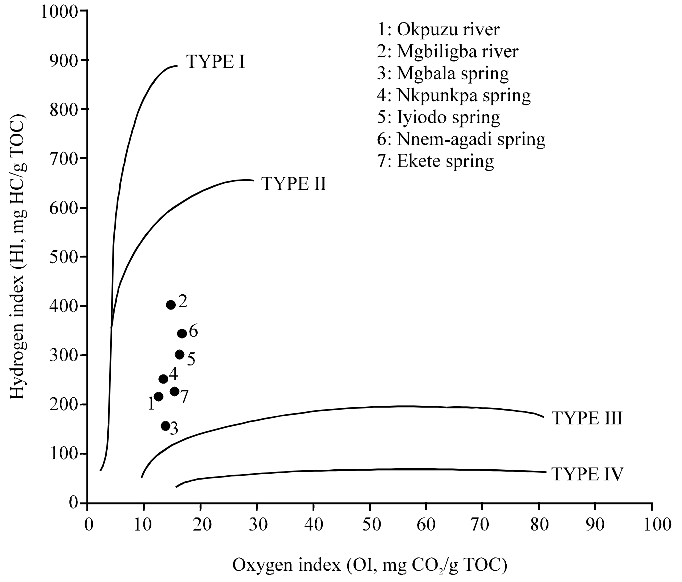

Fig. 5: Plot of HI versus OI showing mainly Type II organic matter compositions

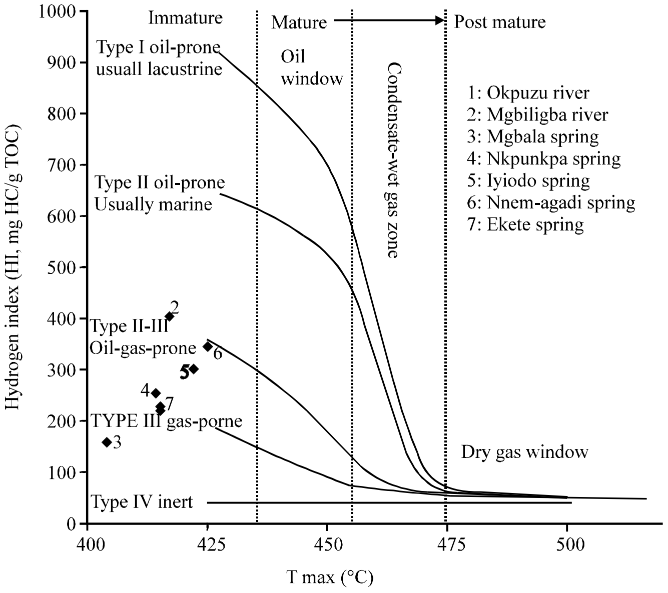

Fig. 6: Plot of HI versus Rock-Eval T_{max} for the lignite samples from the Ogwashi-Asaba Formation

inertinite (H: L: I) ratios of 9:87:4. This indicates a predominance of Type II kerogen with subordinate amount of Type III and Type IV kerogen in the organic matter. Also, the atomic H/C ratios of 1.04-1.55 and O/C ratios of 0.27-0.33 (Table 2) show that the coals plot mainly within the Type II band on a van Krevlen diagram (Fig. 7). Maceral analyses have showed that the lignite samples are moderately rich in liptinite, mostly composed of liptodetrinite, sporinite and cutinite (Table 3). Petersen (2006) and Petersen and Nytoft (2006) observed that humic coals dominated by huminite have proven to be oil-prone. The liptinite macerals are more paraffinic in structure and they are likely to be more oil-prone than the huminite (Akande *et al.*, 2007).

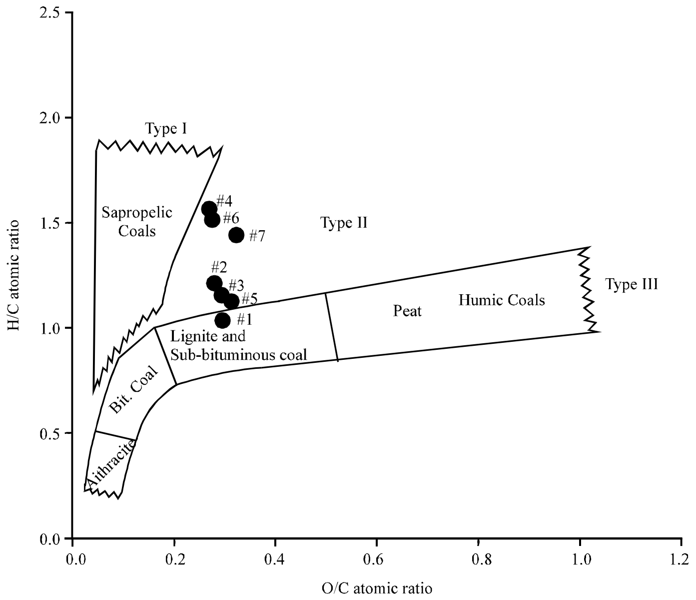

Fig. 7: van Krevlen diagram of atomic H/C versus O/C ratios in samples of the Ogwashi-Asaba Formation showing that the lignites plot within Types II-III and III kerogen band

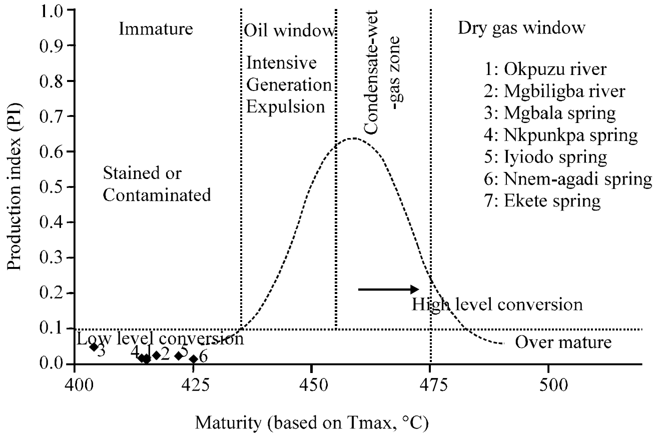

Fig. 8: Plot of PI versus Tmax of the lignite samples from Ogwashi-Asaba Formation

Thermal maturity: The thermal maturity of the lignite samples in the Ogwashi-Asaba Formation was evaluated by pyrolysis-derived indices, such as Rock-Eval Tmax, Production Index (PI) and vitrinite reflectance measurements (Table 1 and 4). Peters (1986) noted that PI and T_{max} values less than 0.1 and 435°C, respectively indicate immature organic matter, while T_{max} greater than 470°C suggest a wet-gas zone. The T max values of the lignites range from 404 to 425°C (averaging 416°C). PI values ranged from 0.02 to 0.05. The vitrinite reflectance values range between 0.24 and 0.36. These values indicate that the samples are thermally immature with respect to petroleum generation. Plot of PI versus T_{max} (Fig. 8), also show that the samples are immature.

The S/C ratio ranges from 0.067 to 0.126, which indicates the presence of pyrite in the samples (Wang *et al.*, 2011). The N/C atomic ratio ranges from 0.006 to 0.02 (Table 2) and these low ratios are characteristic of immature organic matter derived from vascular land plants (Hetenyi *et al.*, 2004). The low values of N/C atomic ratio may also suggest that the preserved organic matter underwent selective degradation during diagenesis and microbial reworking that could have modified the original N/C ratios (Meyers, 1997; Hetenyi *et al.*, 2004; Vandenbroucke and Largeau, 2007). The carbon contents of 61-67% (d.a.f.) of the coals indicate that they are of lignite to sub-bituminous rank (Table 2 and Fig. 7). The sample from Iyiodo Spring is a low-grade coal, whereas, all the others are of high grade. The rank of the lignite samples has been assessed on the basis of bed moisture, huminite reflectance, volatile matter content and gross calorific value. Under the German and American classification schemes (Taylor *et al.*, 1998) the samples are classified as Weich- to Mattbraunkohle and lignite, respectively whereas according to the ECEUN (1998) classification they are characterized as low-rank coals C to B. The van Krevlen diagram (Fig. 7) points to the same result and the high H/C ratios are due to the high liptinite contents of all the samples.

CONCLUSION

The results of this study show that the lignites have appreciable amounts of organic matter (TOC of up to 63.54 wt.%) to generate both oil and gas. The lignites are thermally immature with regards to petroleum generation. The lignites are dominated by huminite but contain high liptinite contents in all the samples and are classified as Type II-III and Type III kerogen by both Rock-Eval and elemental atomic ratios (H/C and O/C). The HI values range from 157 to 402 mg HC/g TOC, suggesting potential for both oil and gas generation.

ACKNOWLEDGMENTS

The author is grateful to Prof. Dr. Kimon Christanis of the Department of Geology, University of Patras, Greece, for his assistance in the chemical analyses. Weatherford Laboratories, Texas, USA, are gratefully acknowledged for the TOC and Programmed Pyrolysis analyses.

REFERENCES

ASTM D3174, 2004. Standard method for ash in the analysis sample of coal and coke from coal. 2004 Annual Book of ASTM Standards, Gaseous Fuels, Coal and Coke. American Society for Testing and Materials, PA, Philadelphia, Vol. 05.06, pp: 322-326.

ASTM D3175, 2004. Standard method for volatile matter in the analysis sample of coal and coke. 2004 Annual Book of ASTM Standards, Gaseous Fuels; Coal and Coke. American Society for Testing and Materials, Philadelphia, PA, Vol. 05.06, pp: 327-330.

ASTM D3302, 2004. Standard method for total moisture in coal. 2004 Annual Book of ASTM Standards, Gaseous Fuels; Coal and Coke. American Society for Testing and Materials, Philadelphia, PA, Vol. 05.06, pp: 352-358.

ASTM D5373, 2004. Standard test methods for instrumental determination of carbon, hydrogen and nitrogen in laboratory samples of coal and coke. 2004 Annual Book of ASTM Standards, Gaseous Fuels; Coal and Coke. American Society for Testing and Materials, Philadelphia, PA, Vol. 05.06, pp: 504-507.

ASTM D5865, 2004. Standard Test Method for Gross Calorific Value of Coal and Coke. Annual Book of ASTM Standards, Gaseous Fuels; Coal and Coke. Vol. 05.06, ASTM, Philadelphia, USA., pp: 519-529.

Akande, S.O., A. Hoffknecht and B.D. Erdtmann, 1992. Rank and petrographic composition of selected upper cretaceous and tertiary coals of Southern Nigeria. Int. J. Coal Geol., 71: 209-224.

Akande, S.O., I.B. Ogunmoyero, H.I. Petersen and H.P. Nytoft, 2007. Source the lower maastrichtian mamu foundation, SE Nigeria. J. Pet. Geol., 30: 303-324.

Benkhelil, J., 1989. The evolution of the cretaceous benue trough, Nigeria. J. Afr. Earth Sci., 8: 251-282.

Chene, Jan du R.E., M.S. Onyike and M.A. Sowunmi, 1978. Some new Eocene pollen of the Ogwashi-Asaba Formation, South-Eastern Nigeria. Revista Espanola Micropaleontol., 10: 285-322.

Clayton, J.L., 1993. Composition of Crude Oils Generated from Coals and Coaly Organic Matter in Shales. In: Hydrocarbons from Coal, Law, B.E. and D.D. Rice (Eds.)., Vol. 38, American Association of Petroleum Geologists Studies in Geology, USA., pp: 185-201.

Davis, R.C., S.W. Noon and J. Harrington, 2007. The petroleum potential of tertiary coals from western Indonesia: Relationship to mire type and sequence stratigraphic setting. Int. J. Coal Geol., 70: 35-52.

Da Swardt, A.M.J., H. Piper, 1957. The lignites of Asaba Division, Benin province. Records of the Geological Survey of Nigeria, pp: 5-23.

Du Preez, J.W., 1945. Geology of Oba and Nnewi lignite deoposits, Onitsha province. Annual Report of Geological Survey of Nigeria, pp: 26-29.

Du Preez, J.W., 1946. Further observation on the lignites of Onitsha province. Annual Report of Geological Survey of Nigeria, pp: 25-26.

ECEUN, 1998. International classification of in-seam coals. Economic Commission for Europe-United Nations, Energy 19, Geneva.

Hendrix, M.S., S.C. Brassell, A.R. Carroll and S.A. Graham, 1995. Sedimentology, organic geochemistry and petroleum potential of jurassic coal measures: Tarim, junggar and turpan basins, Northwest China. Am. Assoc. Pet. Geol. Bull., 79: 929-959.

Hetenyi, M., C. Sajgo, I. Veto, A. Brukner-Wein and Z. Szanto, 2004. Organic matter in a low productivity anoxic intraplatform basin in the Triassic Tethys. Org. Geochem., 35: 1201-1219.

Hunt, J.M., 1991. Generation of gas and oil from coal and other terrestrial organic matter. Org. Geochem., 17: 673-680.

ICCP, 1971. International Handbook of Coal Petrography. 1st Suppl., 2nd Edn., Centre National de la Recherche Scientifique, Paris, France.

ICCP, 2001. The new inertinite classification (ICCP System 1994). Fuel, 80: 459-471.

ISO 7404-2, 2004. Methods for the petrographic analysis of bituminous coal and anthracite-part 2: Method for preparing coal samples. International Organization for Standardization, Geneva, Switzerland, pp: 7.

ISO 7404-5, 2004. Methods for the petrographic analysis of bituminous coal and anthracite-part 5: Method of determining microscopically the reflectance of vitrinite. International Organization for Standardization, Geneva, Switzerland, pp: 12.

Kogbe, C.A., 1976. Paleogeographic History of Nigeria from Albian Times. In: Geology of Nigeria, Kogbe, C.A. (Ed.)., Elizabethan Publishers, Lagos, pp: 237-252.

Langford, F.F. and M.M. Blanc-Valleron, 1990. Interpreting rock-eval pyrolysis data using graphs of pyrolizable hydrocarbons versus total organic carbon. Am. Assoc. Pet. Geol. Bull., 74: 799-804.

Meyers, P.A., 1997. Organic geochemical proxies of paleoceanographic, paleolimnologic and paleoclimatic processes. Org. Geochem., 27: 213-250.

Mpanju, F., S.J. Ntomola and M. Kagya, 1991. The source rock potential of the karoo coals of the south western rift basin of Tanzania. J. Southeast Asian Earth Sci., 5: 291-303.

Murat, R.C., 1972. Stratigraphy and Paleogeography of the Cretaceous and Lower Tertiary in Southern Nigeria. In: African Geology, Dessauvagie T.J.F. and A.J. Whiteman (Eds.)., University of Ibadan Press, Africa, pp: 251-266.

Murchison, D.G., 1987. Recent advances in organic petrology and organic geochemistry: an overview with some reference to oil from coal. Geol. Soc. Spec. Publ., 32: 257-302.

Nwachukwu, S.O., 1972. The tectonic evolution of the southern portion of the benue trough, Nigeria. Geol. Mag., 109: 411-419.

Nwadinigwe, C.A., 1992. Wax and resin characteristics of Nigeria's lignites and sub-bituminous coals. J. Min. Geol., 28: 75-80.

Nwajide, C.S., 1980. Eocene tidal sedimentation in the anambra basin, southern Nigeria. Sediment. Geol., 25: 189-207.

Obaje, N.G. and H. Hamza, 2000. Liquid hydrocarbon source-rock potential of mid-Cretaceous coals and coal measures in the middle benue trough of Nigeria. J. Afr. Earth Sci., 89: 130-139.

Obaje, N.G., H. Wehner, G. Scheeder, M.B. Abubakar and A. Jauro, 2004. Hydrocarbon prospectivity of Nigeria's inland basins: From the viewpoint of organic geochemistry and organic petrology. AAPG Bull., 87: 325-353.

Oboh-Ikuenobe, F.E., C.G. Obi and C.A. Jaramillo, 2005. Lithofacies, palynofacies and sequence stratigraphy of Palaeogene strata in southern Nigeria. J. Afr. Earth Sci., 41: 79-101.

Obaje, N.G., 2009. Geology and Mineral Resources of Nigeria. Springer, Heidelberg, Pages: 221.

Okezie, C.N. and S.A. Onuogu, 1985. The lignites of Southeastern Nigeria. A Summary of Available Information. Geological Survey of Nigeria Occasional.

Olade, M.A., 1975. Evolution of the Nigeria's benue trough (aulacogen): A tectonic model. Geol. Mag., 112: 575-583.

Olobaniyi, S.B. and J.E. Ogala, 2011. Major and trace element characteristics of the Tertiary lignite series within the Ogwashi-Asaba Formation, southern Nigeria. Proceedings of the 23rd Colloquium of African Geology/14th Conference of the Geological Society of Africa Johannesburg, January 8-14, 2011, South Africa,.

Orajaka, I.P., G. Onwemesi, B.C.E. Egboka, G.I. Nwankor, 1990. Nigerian coal. Min. Maga., 162: 446-451.

Peters, K.E. and M.R. Cassa, 1994. Applied source rock geochemistry. The petroleum system-from source to trap magoon. Am. Assoc. Pet. Geol. Mem., 60: 93-117.

Peters, K.E., 1986. Guidelines for evaluating petroleum source rock using programmed pyrolysis. AAPG Bull., 70: 318-329.

Petersen, H.I. and H.P. Nytoft, 2006. Oil generation capacity of coals as a function of coal age and aliphatic structure. Organic Geochem., 37: 558-583.

Petersen, H.I., 2006. The petroleum generation potential and effective oil window of humic coals related to coal composition and age. Int. J. Coal Geol., 67: 221-248.

Reyment, R.A., 1965. Aspects of Geology of Nigeria. University of Ibadan Press, Ibadan, Nigeria, pp: 133.

Short, K.C. and A.J. Stauble, 1967. Outline of geology of Niger Delta. AAPG Bull., 51: 761-779.

Simpson, A., 1949. The lignite seams of asaba division, benin province: Annual Report of Geological Survey of Nigeria. Government of Nigeria, pp: 6-14.

Simpson, A., 1954. The Nigerian coal field: The geology of parts of Onitsha, Owerri and Benue provinces. Geol. Survey Nig. Bull., 24: 85-85.

Sykes, R. and L.R. Snowdon, 2002. Guidelines for assessing the petroleum potential of coaly source rocks using Rock-Eval pyrolysis. Org. Geochem., 33: 1441-1455.

Sykorova, I., W. Pickel, K. Christanis, M. Wolf, G.H. Taylor and D. Flores, 2005. Classification of huminite-ICCP System 1994. Int. J. Coal Geol., 62: 85-106.

Taylor, G.H., M. Teichmuller, A. Davis, C.F.K. Diessel, R. Littke and P. Robert, 1998. Organic Petrology. Gebruder Borntraeger, Berlin, Pages: 704..

Tissot, B.P. and D.H. Welte, 1984. Petroleum Formation and Occurrence. 2nd Edn., Springer-Verlag, Berlin, ISBN: 0387132813, pp: 699.

Vandenbroucke, M. and C. Largeau, 2007. Kerogen origin, evolution and structure. Org. Geochem., 38: 719-833.

Wang, L., C. Wang, Y. Li, L. Zhu and Y. Wei, 2011. Organic geochemistry of potential source rocks in the Tertiary Dingqinghu Formation, Nima Basin, Central Tibet. J. Pet. Geol., 34: 67-85.

Wilson, R.C., 1924. Brown coal in Nigeria. Occasional Paper Number 1 of Geological Survey of Nigeria. Government of Nigeria, pp: 1-15.