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ORIGINAL PAPER

Rock-Eval pyrolysis and organic petrographic analysis of the Maastrichtian coals and shales at Gombe, Gongola Basin, Northeastern Nigeria

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Abstract The Gongola Basin forms one of the inland Cretaceous to tertiary sedimentary basins in Nigeria with relatively unknown petroleum system. In this study, the investigated source rock intervals of the Maastrichtian Gombe Formation are located at the Maiganga coal mine, near Gombe, Gongola Basin, Nigeria. The exposed part of the mine consists of about 35-m thick coarsening upward section with the basal part made up of coal and shale interbeds while the upper part consists of siltstone and sandstone and probably deposited in fluvio-deltaic environment. The coal and interbedded shale appear most prospective source rock facies in the formation and were evaluated with respect to their hydrocarbon source rock potential. The organic geochemical results showed high TOC for the coals (37.71–65.29 wt%) and moderate organic carbon concentration (1.19–4.81 wt%) for the shales. S_2 values ranges from 57.96 to 103.21 mgHC/g rock and 0.51–6.22 mgHC/g rock for the coal and shales, respectively. The HI is less than 200 mgHC/gTOC in all the coal and shale samples suggesting Type III kerogen and predominant plant contributions from terrestrial sources. Consequently, gaseous hydrocarbon potential is exhibited in the source beds. The organic petrography shows vitrinite as dominant maceral followed by inertinites and liptinites with inorganic minerals like pyrite and kaolinite. The Tmax is less than 435 °C in all the samples indicating pre-oil window stage; this is corroborated by the Romax value ranging from 0.45 to 0.55 %. Plot of PI against Tmax indicates low level organic matter conversion while the vitrinite reflectance values suggest a sub-bituminous coal. The study suggests that the investigated coal and shale samples constitute good source rock and have potential for gas. The generally low HI in the coals and the associated shales indicate more allochthonous and hydrogen poor organic matters in the source beds. Maceral composition of the coals suggests wet swamp environment and predominance of arborescent vegetation type. At present level, the organic matters are immature to marginally mature deeper level equivalents might have generated gas.

Keywords Deltaic · Facies · Formation · Kerogen · Maceral · Maiganga

Introduction

Gongola Basin forms part of the northeastern extension of the major Benue Rift basins in Nigeria. The major coal resources of Nigeria occur within the Benue Trough in the following areas; Enugu, Benue, Nasarawa, Kogi and Gombe States (Fig. 1) and coal deposits have been reported in various localities Doho, Kumo, Warji and Haman Gari in the Gongola Basin (Jauro et al. 2007). The present study area is located at Maiganga coal mine, Gombe and the coal which constitutes one of the litho-units of the Maastrichtian Gombe Formation is presently being mined for firing kiln at Ashaka Cement Factory located about 100 km north of Gombe town.

Peters et al. (2005) defined coal as having more than 50 wt% organic matter. In recent time, attempts have been made to examine the potentiality of coals as source of hydrocarbon in various part of the world (Hendrix et al. 1995; Petersen et al. 2000; Boreham et al. 2003), and some of the studies showed the potential of non-marine coals as

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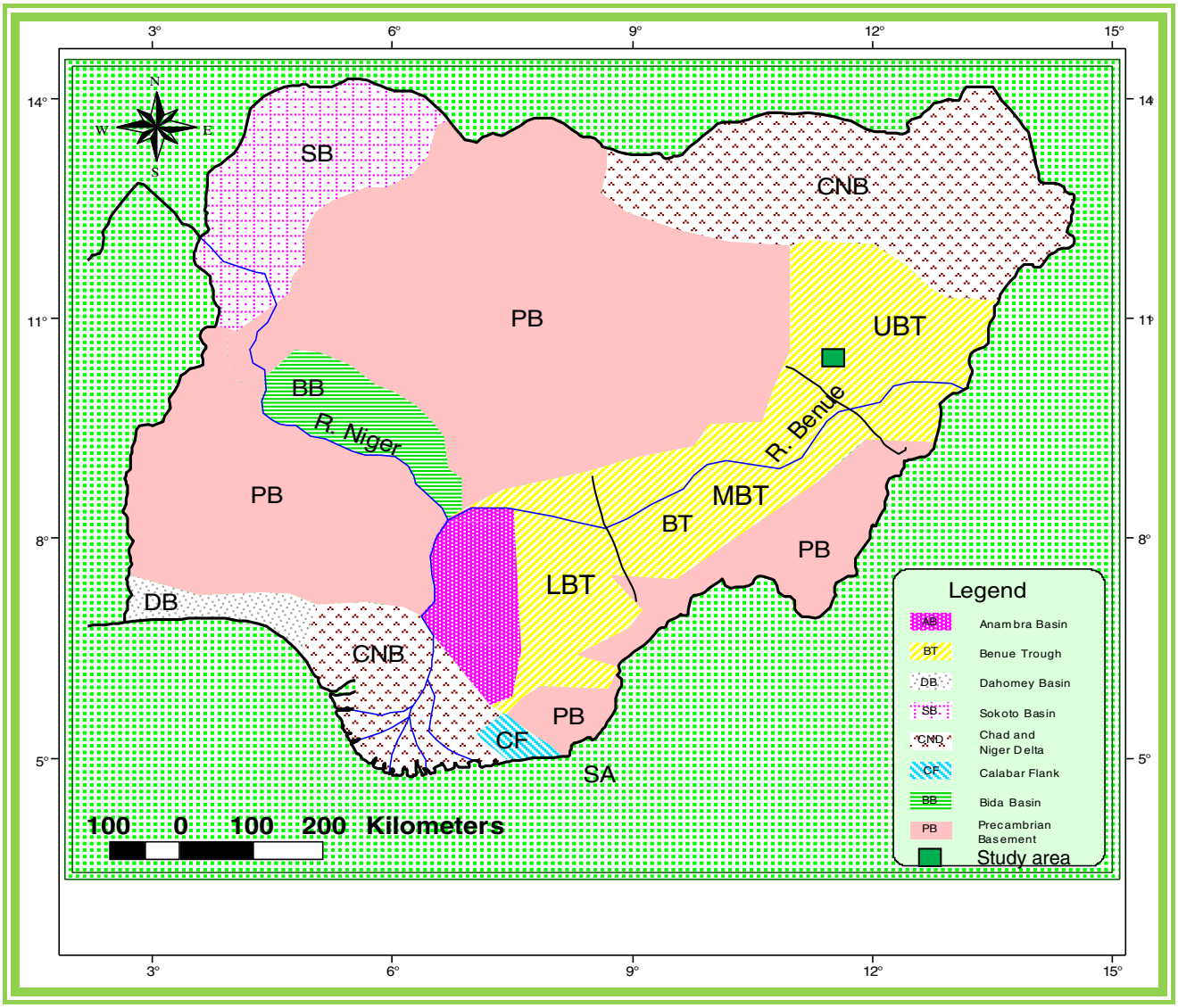


Fig. 1 Geological map of Nigeria showing the basement complex and the sedimentary basins (modified after Obaje et al. 2004). Note that LBT, MBT and UBT denote Lower Benue Trough, Middle Benue Trough and Upper Benue Trough, respectively

hydrocarbon source rocks under sufficient thermal evolution (Betrand et al. 1986). Improved understanding of geochemical and petrological characteristics of coal through organic petrography, Rock-Eval pyrolysis and Gas Chromatography has shown coal as a possible candidate for liquid hydrocarbon generation (Clayton et al. 1991; Hunt 1991). In the southern and central part of Nigeria, similar studies have also been carried out on some coal and lignite deposits (Obaje et al. 2004; Akande et al. 2007). Akande et al. (2015) recently reported that the Tertiary Ogwashi Asaba lignite are enriched in liptinitic maceral particularly the resinite and had contributed to oil reservoired in the Agbada Formation of Niger Delta.

The geochemical and petrological characteristics of the Maiganga coal and the associated shales are relatively unknown despite its extensive occurrence. The objectives of this study are to evaluate the source rock characteristics, hydrocarbon potential of the coal and shale as well as depositional environment in the study area using parameters such as total organic carbon (TOC), Rock-Eval pyrolysis, maceral analysis and vitrinite reflectance. Our new data on the organic petrographic characteristics of the coals provide evidence for constraining the thermal history and rank of the coal and the quality of the organic matters.

Geologic setting of Benue Trough and stratigraphic framework

The Benue Trough of Nigeria is a rift basin in central West Africa extending NNE-SSW for about 800 km in length and

150 km in width. The trough contains up to 6000 m of Cretaceous–Tertiary sediments of which those pre-dating the mid-Santonian have been compressionally deformed, faulted and uplifted in several places. The Benue Trough is subdivided into a lower, middle and an upper portion (Fig. 1). The Upper Benue Trough can be subdivided into the east–west trending Yola Basin (or "Arm") and the north–south trending Gongola Basin (Fig. 2). The evolution of the Benue Trough had been linked with the opening of the Atlantic which began with the separation of South America from Africa plates in the Carboniferous through the seafloor spreading consequent to continental up-doming and rifting (Wright 1968). Olade (1975) also presented the spreading ridge hypothesis and applied the Y-shaped triple junction rift model (R-R-R) to the break-up of African and South American plates in which two arms of the triple rift junction continued to spread while the spreading in the third arm was aborted. According to this model, the three radial rift systems that met at an RRR triple junction in the Gulf of Guinea became active during the early Cretaceous. The south Atlantic, the Gulf of Guinea and the Benue Trough represent rift arms of this triple junction.

The stratigraphy of the Gongola Basin starting from the oldest consists of the basement rocks, Bima Formation (feldspathic sandstones), Yolde Formation (sandstones, shales and limestones), Pindiga Formation (shales and fossiliferous limestones), Gombe Formation (sandstones, siltstones, shales, ironstones and coal seams), Kerri Kerri Formation (sandstones) and the alluvium.

The Gombe Formation is a heterogeneous sequence consisting essentially of sandstones, siltstones, shales, and coals. It attains maximum thickness of over 600 m in some parts of the sub-basin and has been dated Maastrichtian overlying the marine Turonian to Coniacian Pindiga Formation. It has been consistently interpreted as fluvio-deltaic sediments by various authors (Ojo 1999; Ojo and Akande 2004).

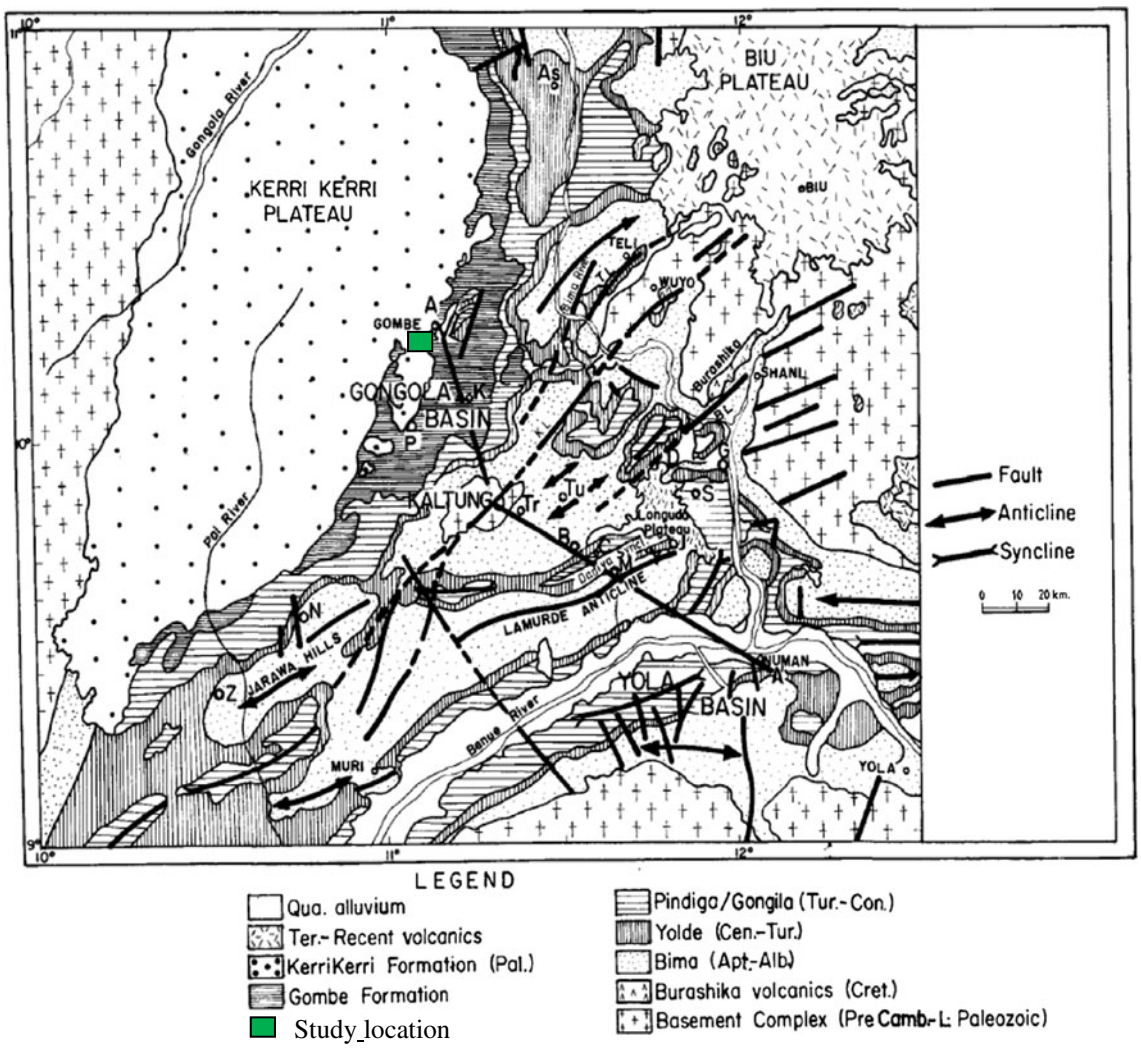


Fig. 2 Simplified geological map of the Upper Benue Rift Basins showing N-S trending Gongola Basin (After Akande and Erdtmann 1998)

Methodology

Field sampling and lithology

Twenty-two (22) samples of coals and shales were obtained from Maiganga coal mine. The Maiganga coal mine is an open pit of about 35 m deep, consisting of shales, coal, sandstone, siltstone and intercalations of ironstone concretions. The sections were logged from the base to the top (Fig. 3). There were obvious changes in the lithologic units during logging which shows different physical changes such as changes in texture, geometry and colour.

Total organic carbon

Twenty-one samples of coals and shales were analysed for total organic carbon (TOC) by means of the LECO CS 230 carbon analyser. Twenty grammes of the pre-cleaned samples were crushed and accurately weighed into clean LECO crucibles. The rocks were then de-mineralized by hot 10 % HCl and afterwards repeatedly with distilled water. After drying at 60 °C, the crucibles were automatically introduced into the furnace for combustion and measurement of the organic carbon content.

Rock-Eval pyrolysis

Nine coal samples, 11 shale samples and one coaly shale were analysed by means of a Rock-Eval-6 pyrolyser at Weatherford laboratories Canada. Each pre-cleaned portion of the samples was crushed in mortal using pestle and weighed accurately (100 mg approx.) into the sample holder. The process involved the transfer of each sample into the furnace where it was heated initially at 300 °C for 3 min in an atmosphere of helium to release the free hydrocarbons (S_1). Pyrolysis of the bound hydrocarbons to give S_2 peak followed immediately as the oven temperature was ramped up rapidly to 550 °C at the rate of 25 °C/min. Both the S_1 and S_2 hydrocarbon peaks were measured using a flame ionization detector (FID). A splitting arrangement permitted the measurement of S_3 peak (carbon dioxide) by means of a thermal conductivity detector (TCD). The following parameters are obtained through measurements; (S1, S2, S3, TOC, Tmax). HI, OI, S2/S3, GP and PI were however derived.

Organic petrography

Three samples of coal were subjected to petrographic analysis which was carried out at Pearson coal petrography in Canada. The determination of macerals content was reflected by light

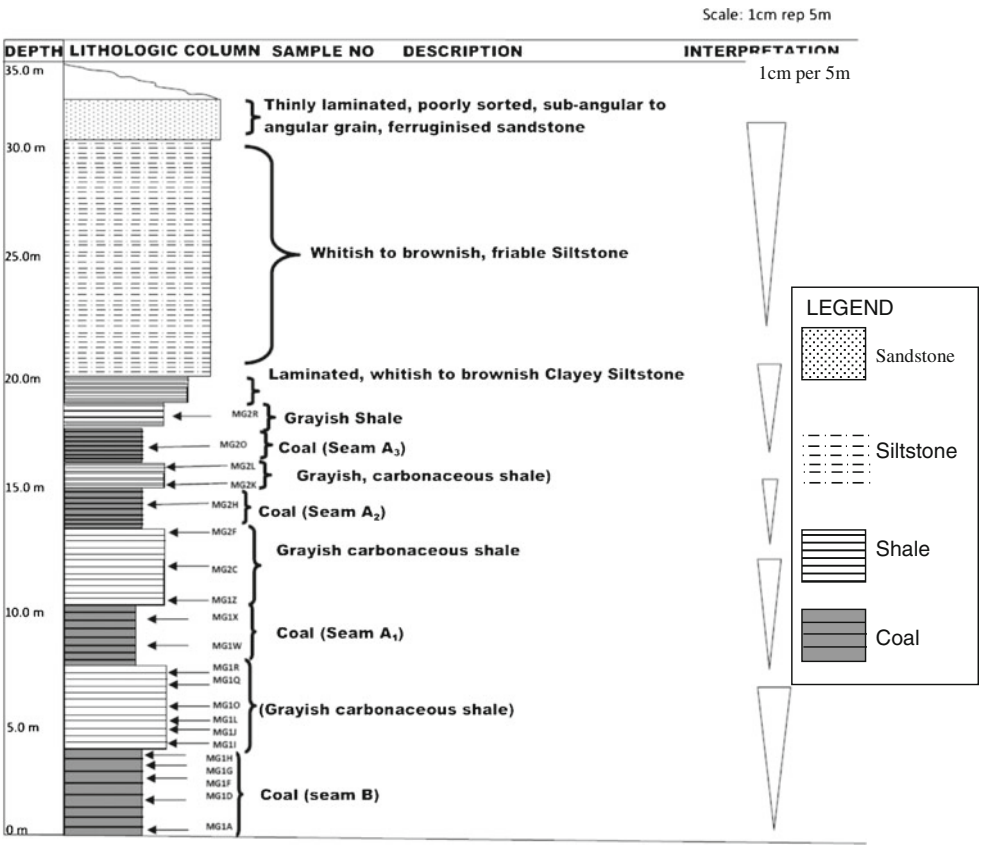


Fig. 3 Lithologic succession of Gombe Formation at the Maiganga mine. The succession coarsens upward from coal, shale, siltstone to sandstone

microscopy. The polished sections of the selected samples were made from crushed samples mounted in epoxy resin. The polished briquettes were prepared from crushed 1-mm-size samples representing each sample, which was then mounted in epoxy resin. Ordinary white reflected light from a tungsten lamp and violet-blue light from a high-pressure mercury lamp to initiate fluorescence were used for illumination. Maceral observation was carried out on a Leitz MPV-2 photomicroscope. Maceral composition was determined by means of a swift automatic point counter; each composition is based on at least 500 counts.

Results and discussion

The results of the TOC and Rock-Eval data are presented in Table 1 while the summarized organic petrographic data is presented in Table 2.

Organic source richness

The minimum organic content of sediments which eventually becomes a source bed of petroleum generally ranges between 0.5 % for shale, 0.3 % for carbonates and 1.0 % for clastic rocks (Killops and Killops 1993). TOC value of 1.5 to 2 % has generally been accepted for defining good source rocks (Hunt 1996). The threshold of S1 + S2 (genetic potential) greater than 2 mgHC/g rock can also be considered as prerequisite for classification as a possible oil source rock (Bissada 1982). However, in the samples analysed, the TOC values range from 1.19 to 4.81 wt% for the shale, 37.71 to 65.29 wt % for the coal and 16.35 wt% for coaly shale indicating very good to excellent source rock (Table 1).

The high TOC values in the coal generally suggest that the condition during deposition was favourable for organic matter production and preservation. The genetic potential of the shale range from 0.56 to 6.39 mg/g with an average of 2.57 mg/g, values for coal range from 59.45 to 107.02 mg/g with an average of 86.17 mg/g while the coaly shale has genetic potential value of 13.99 mg/g indicating a good source rock (Tissot and Welte 1984; Peters et al. 2005). The average S2 values of the shale and coal are 2.49 and 83.21 mgHC/g, respectively, confirming the richness of the source rocks. The Onyeama, Okaba and Owukpa coals in the Lower Benue Trough have TOC and S2 values ranging from 60 to 78 wt% and 137 to 195 mgHC/g, respectively, while Jangwa coal in middle Benue Trough has TOC and S2 ranging from 2.69 to 79.1 wt% and 1.99 to 207 mgHC/g, respectively. This further confirms the richness of source rocks in the whole of Benue Trough (Obaje et al. 2004).

Table 1 TOC and Rock-Eval data for coal and shale samples from Maiganga mine

S/n	Sample no/code	Lithology	TOC wt%	S1	S2	S3	Tmax (°C)	HI	OI	S2/S3	PI	S1/TOC	Gp (S1 + S2)
1	MG1A	Coal	63.5	2.89	102.39	16.47	418	162	26	6.2	0.03	5	105.28
2	MG1D	Coal	63.39	1.49	57.96	12.12	416	90	19	4.8	0.03	2	59.45
3	MG1F	Coal	60.67	2.31	75.59	11.40	421	125	19	6.6	0.03	4	77.9
4	MG1G	Coal	65.29	2.09	71.02	12.87	413	109	20	5.5	0.03	3	73.11
5	MG1H	Coal	62.46	3.81	103.21	15.35	420	165	25	6.7	0.04	6	107.02
6	MG1W	Coal	64.22	3.51	88.63	20.99	418	138	33	4.2	0.04	5	92.14
7	MG1X	Coal	59.30	3.34	91.36	18.84	419	154	32	4.8	0.04	6	94.7
8	MG2H	Coal	62.75	3.11	87.59	16.47	422	140	26	5.3	0.03	5	90.7
9	MG2O	Coal	37.71	4.11	71.16	20.42	417	189	54	3.5	0.05	11	75.27
10	MG2K	C. Shale	16.35	0.27	13.72	1.85	426	84	11	7.4	0.02	2	13.99
11	MG1I	Shale	2.11	0.05	1.35	1.29	430	64	61	1.0	0.04	2	1.4
12	MG1J	Shale	2.13	0.05	0.72	1.34	419	34	63	0.5	0.06	2	0.77
13	MG1L	Shale	1.78	0.05	0.51	0.83	425	29	47	0.6	0.09	3	0.56
14	MG1O	Shale	1.85	0.01	0.84	1.18	431	45	64	0.7	0.01	0.5	0.85
15	MG1Q	Shale	1.19	0.05	0.92	0.63	430	77	53	1.5	0.05	4	0.97
16	MG1R	Shale	2.15	0.06	2.48	1.03	426	115	48	2.4	0.02	3	2.54
17	MG1Z	Shale	2.95	0.11	3.31	2.07	428	112	70	1.6	0.03	4	3.42
18	MG2C	Shale	2.99	0.05	2.32	1.65	428	78	55	1.4	0.02	2	2.37
19	MG2F	Shale	3.91	0.10	3.58	2.06	425	92	53	1.7	0.03	3	3.68
20	MG2L	Shale	4.81	0.14	5.14	2.52	429	107	52	2.0	0.03	3	5.28
21	MG2R	Shale	3.84	0.17	6.22	1.79	430	162	47	3.5	0.03	4	6.39

Table 2 Petrographic and vitrinite reflectance values of the investigated Maiganga coal samples

Code	Seam	Depth	Romax	R.R	Reactive components (%)			Inert components (%)				m.m
		(m)	(%)	(%)	Liptinite	Vitrinite	R. semi-fusinite	I. semi-fusinite	Fusinite	Inertodetrinite	Inertinite (%)	(%)
MG2H	Seam A1	21	0.48	0.45	1.3	70.1	9.1	9.3	4.9	0.2	23.5	5.1
MG1W	Seam A2	26	0.49	0.46	1.9	59.3	13.9	13.9	5.9	0.2	33.9	4.9
MG1D	Seam B	33	0.55	0.52	0.4	41.4	21.9	21.9	9.3	0.2	53.3	4.9

F.C fixed carbon (as received), *Romax* percent mean maximum vitrinite reflectance, *R.R* random reflectance, *m.m* mineral matter

Organic matter quality

Hydrogen index (HI) is an important geochemical parameter used to assess quality of organic matter (Van Krevelen 1961). The value of HI of the shale source rocks (29 to162 mgHC/gTOC) is lower than that of the coaly source rock (90 to 189 mgHC/gTOC) (Table 1). This is because much of the hydrocarbons may be adsorbed by the matrix of the coal (Langford and Blanc-Valleron 1990). The HI of both coal and shale samples shows that the organic matter is type III which is capable of generating gas. This is corroborated by the S2/S3 value which ranges from (0.5 to 7.4) a ratio indicative of type III kerogen. Plots of S2 against TOC and hydrogen index (HI) against oxygen index (OI) known as Van krevelen diagram (Figs. 4 and 5) were used to constrain the type of organic matter in the investigated source beds (Langford and Blanc-Valleron 1990). The maceral content of the coals reveals that vitrinite is the most abundant confirming type III organic matter sourced from terrestrial land plants.

Hydrocarbon potential

The hydrocarbon potential (S2) of the samples range from 0.51 to 6.22 mgHc/g, 57.96 to 103.21 mgHC/g and 13.72 mgHC/g for the shale, coal and coaly shale, respectively, indicating good to excellent hydrocarbon potential. The genetic potential calculated for the samples, 0.56–6.39 mgHC/g for the shale, 59.45–107.02 mgHC/g for coal and 16.35 mgHC/g for coaly shale (Table 1), suggests good source rock for most of the samples.

Petroleum generation from coal source rocks and its type are fundamentally dependent on the availability of hydrogen (Hunt 1996; Petersen and Nytoft 2006). Many authors have focused on the importance of liptinite in estimating the

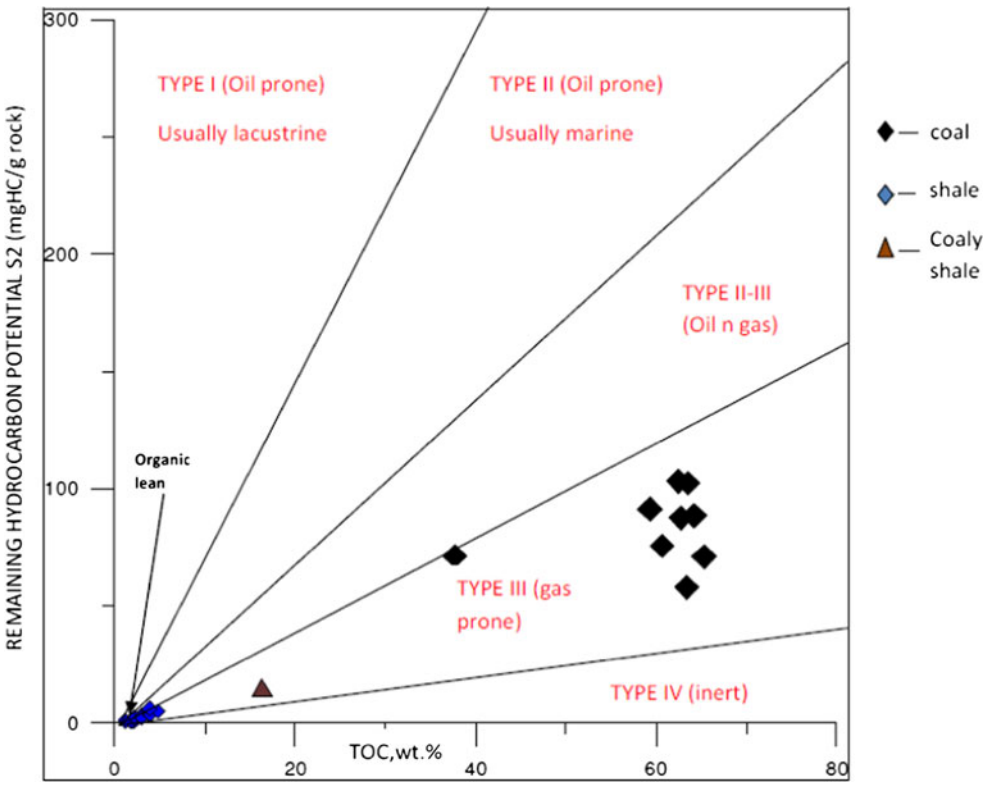


Fig. 4 S2 versus TOC plots for coal and shale samples of Maiganga coal mine, Gongola Basin. The plot indicates type III kerogen (gas prone) for the samples. The shale samples are organically lean

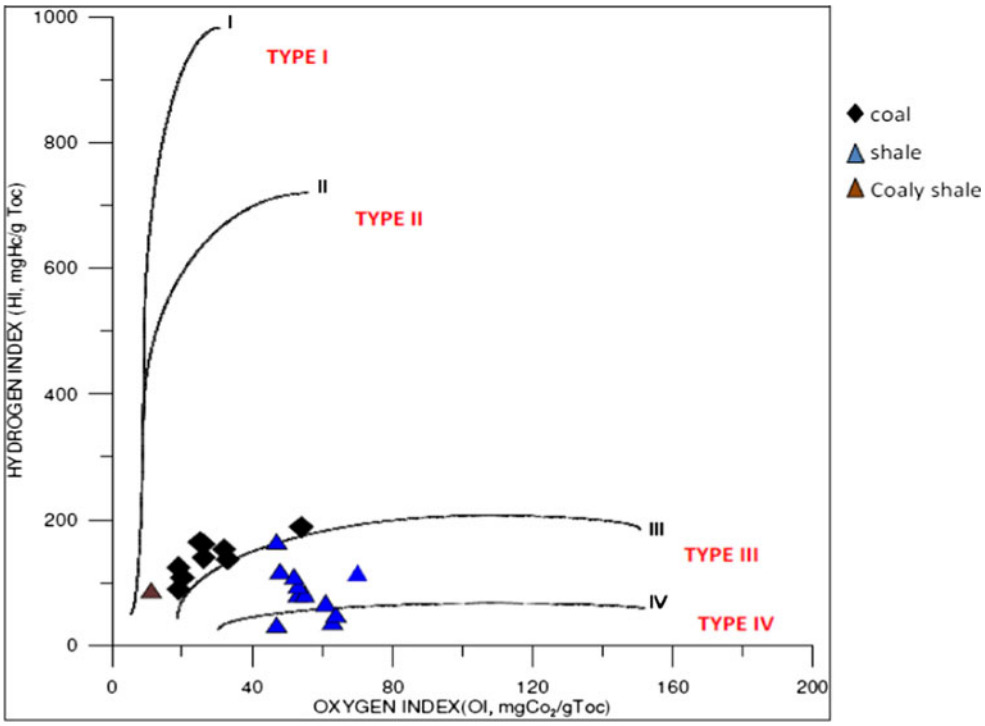


Fig. 5 Plot of HI versus OI for the classification of kerogen (1-1V) of coal, coaly shale and shale samples from Maiganga mine, Gongola Basin. Most of the samples fall within type III kerogen (gas prone) typical of terrestrial source organic matter (After Van Krevelen 1961)

potential of the coal to generate liquid hydrocarbon. Hunt (1991) has suggested 15–20 % liptinite, Snowdon (1991) proposed 10 % hydrogen rich maceral while Mukhopadhyay and Hatcher (1993) suggest 15–20 % liptinite content for a coal to generate oil. In this study, none of the samples has liptinic maceral up to 15 wt% (Table 2). Qin et al. (1993) proposed the potential of maceral to generate hydrocarbon was in the order alginite > resinite > cutinite > sporinite > sub-

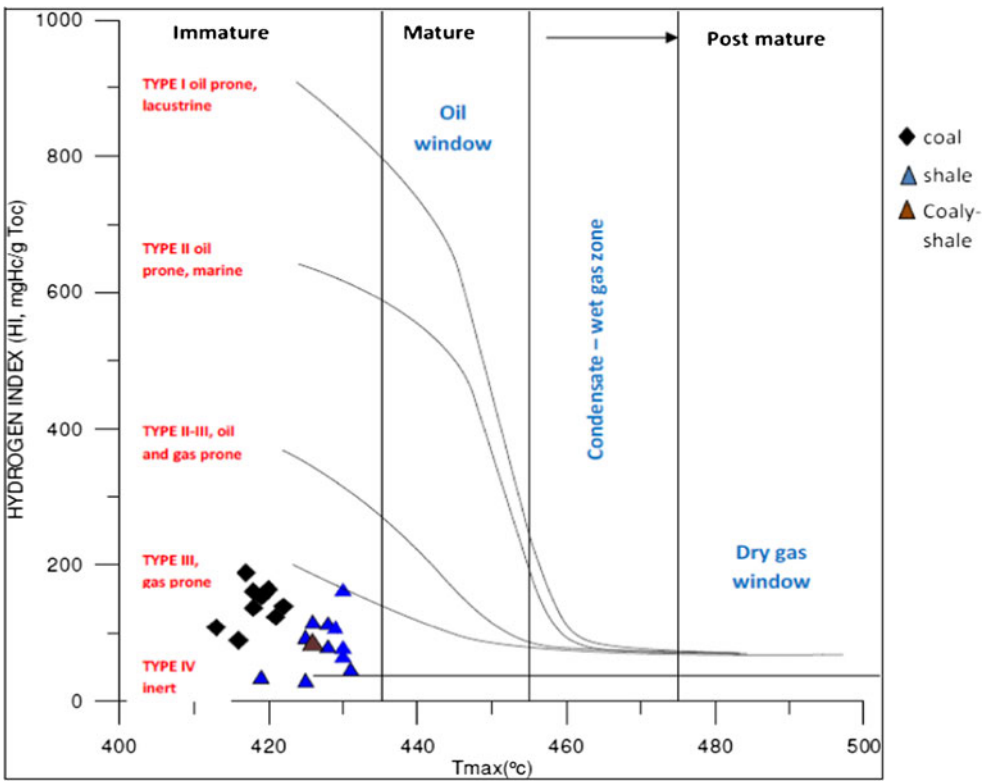


Fig. 6 Plot of hydrogen index (HI) against Tmax of coal, coaly shale and shale samples from Maiganga mine, Gongola Basin. Most of the samples are immature and fall within type III kerogen (gas prone) typical of terrestrial sourced organic matter

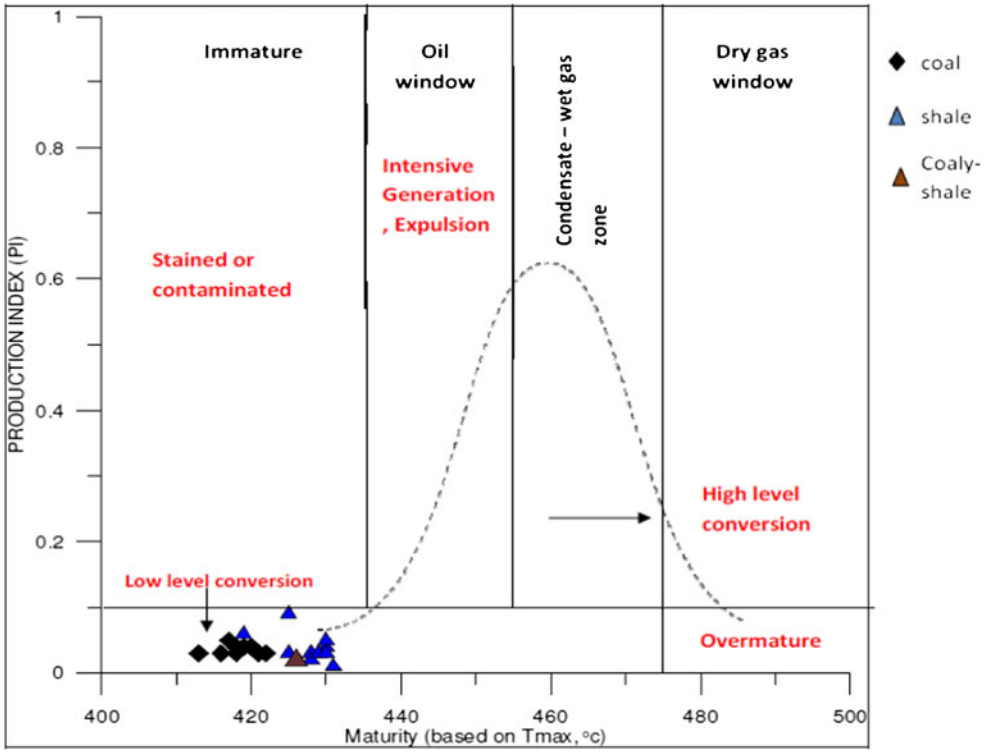


Fig. 7 Plot of hydrogen index (HI) against vitrinite reflectance. The coal samples are immature

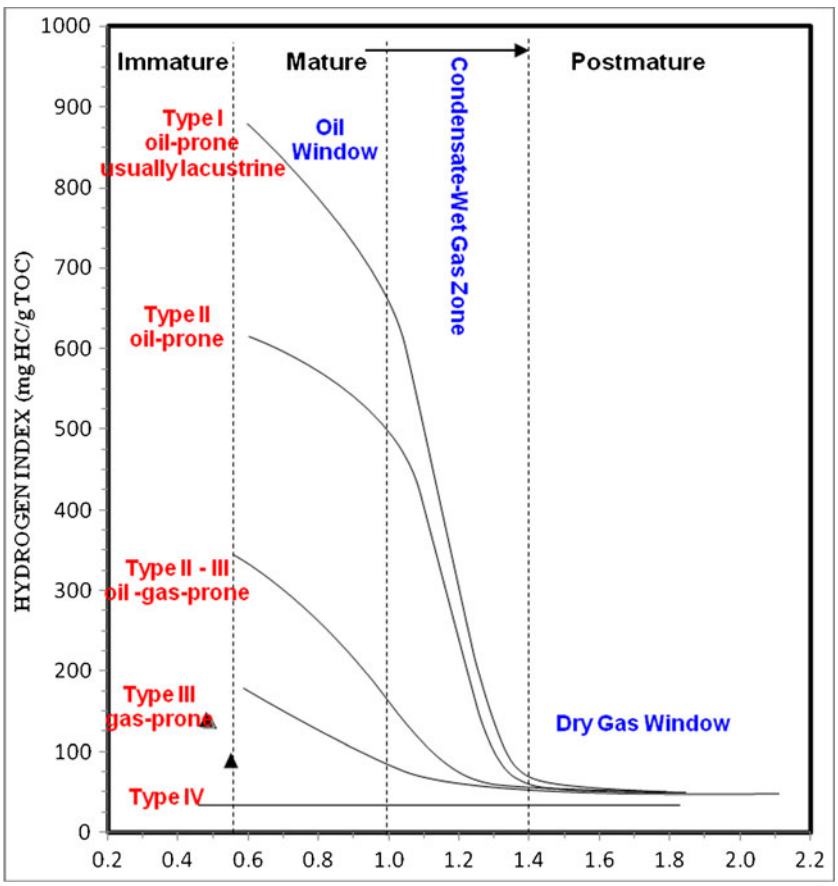


Fig. 8 Plot of production index (PI) against Tmax of coal, coaly shale and shale samples from Maiganga mine, Gongola Basin. All the samples are immature and have low level conversion of kerogen to oil

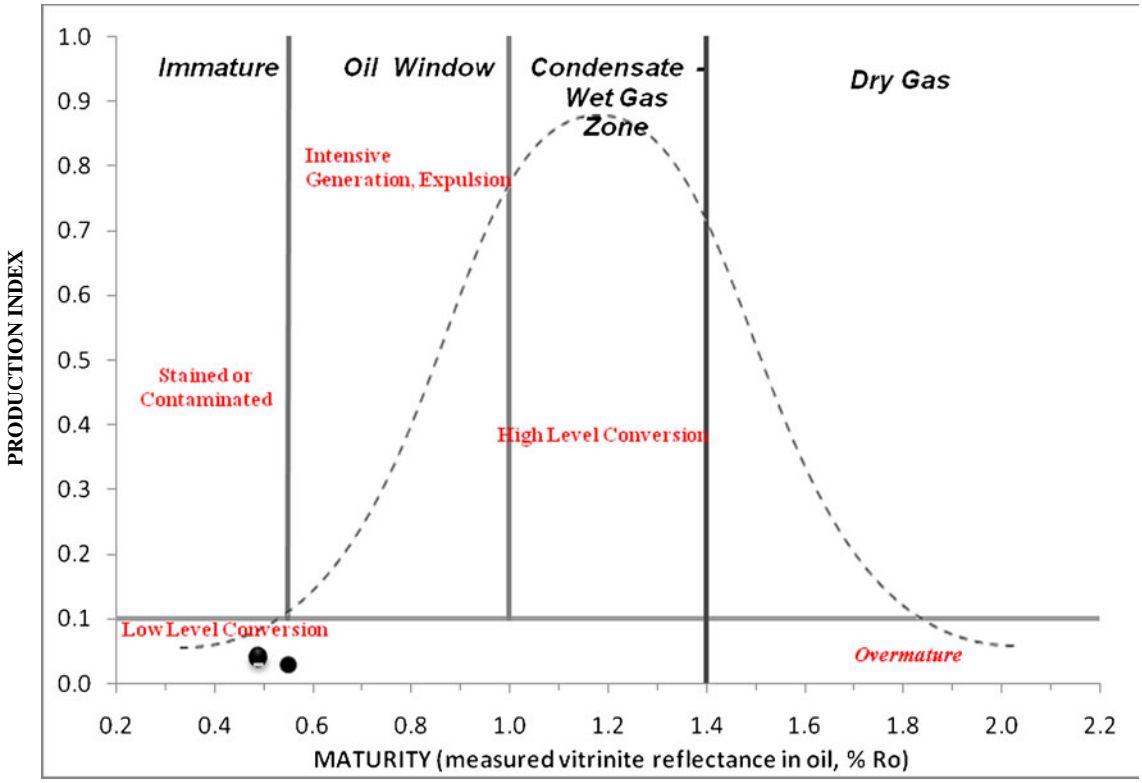


Fig. 9 Plot of production index against vitrinite reflectance for coal samples. Note that the coal samples have low level conversion of kerogen to oil

erinite > vitrinite and inertinite based on abundance of aliphatic carbons in ^{13}C NMR in some group of purified macerals. It is evident that the hydrogen component increases and favour hydrocarbon generation. Isaksen et al. (1998) also stated that

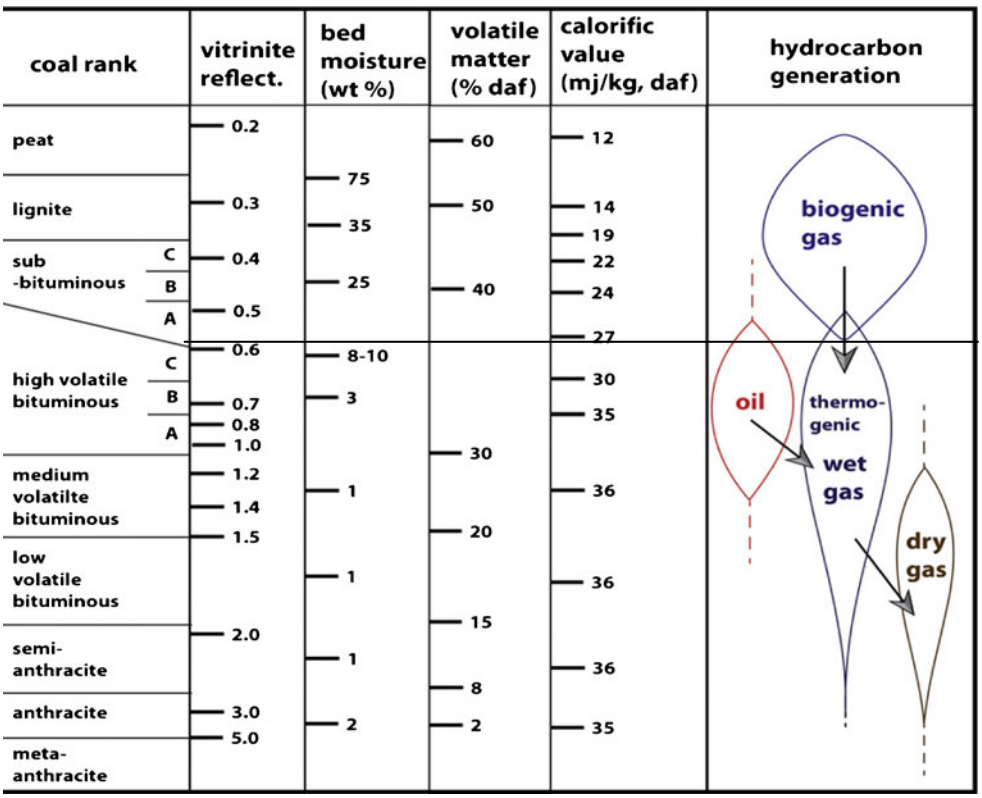


Fig. 10 Correlation of different rank parameters. Note that the Ro value (0.48–0.55) corresponds to coalification rank of sub-bituminous B to A which is capable of generating gas (biogenic). Modified after Hunt (1996)

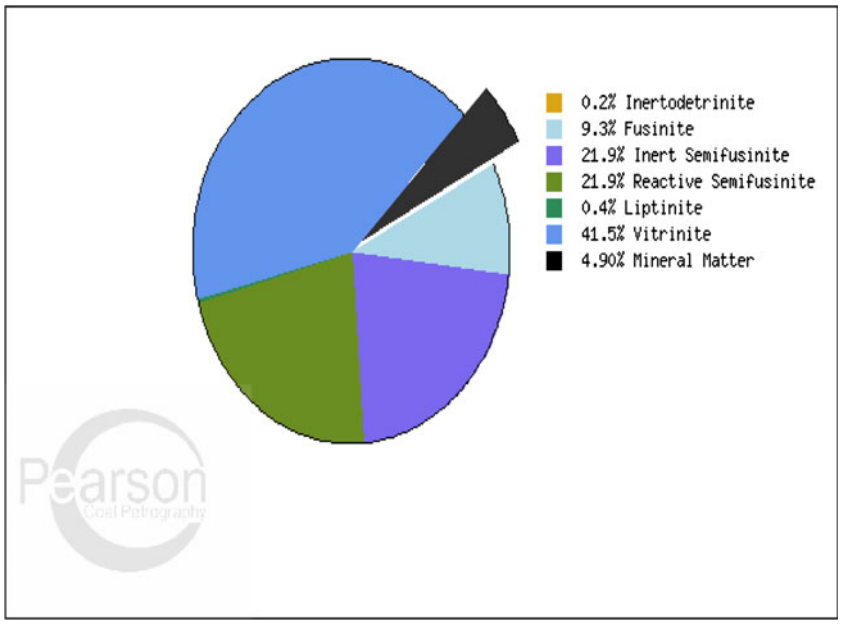


Fig. 11 Maceral pie-chart for sample MG1D (seam B)

the oil expulsion efficiency of coal is dependent on the coals' ability to generate long chain aliphatic component (C_{20}-C_{25}) because the coal structure has a direct influence on the type of petroleum which can be generated. Aliphatic hydrocarbons are associated with liptinite macerals, e.g. alginite, cutinite, suberinite, sporinite, liptodetrinite and resinite. Perhydrous vitrinite in coals (coals with higher percentage of hydrogen plotted above the band of 4.4 to 5.6 in the Seyler's coal chart) could also generate liquid hydrocarbon (Van Krevelen 1993). The predominance of vitrinite maceral and low liptinite content in the investigated samples suggests that the Maiganga coal has the potential to generate only gaseous hydrocarbon. Further probe of the nature of the vitrinite maceral may however give an indication of possible liquid hydrocarbon as oil prone vitrinite rich and liptinite poor coals have been reported in New Zealand (Newman and Newman 1982; Killops et al. 1994, 1998; Newman et al. 1997; Norgate et al. 1997) and Upper Cretaceous coal of San Juan Basin, New Mexico (Clayton et al. 1991) where the vitrinite maceral have been confirmed to be perhydrous.

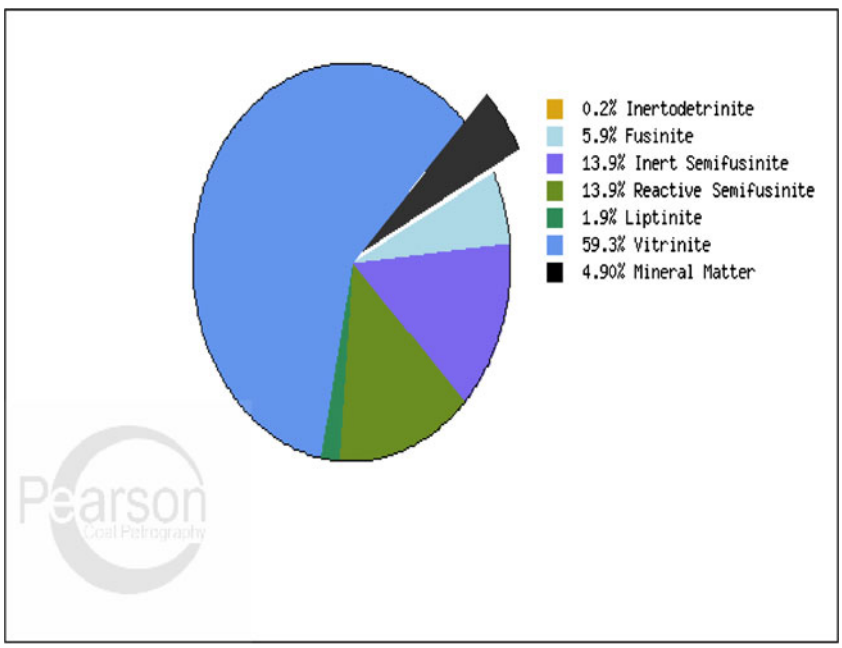


Fig. 12 Maceral pie-chart for sample MG1D (seam A)

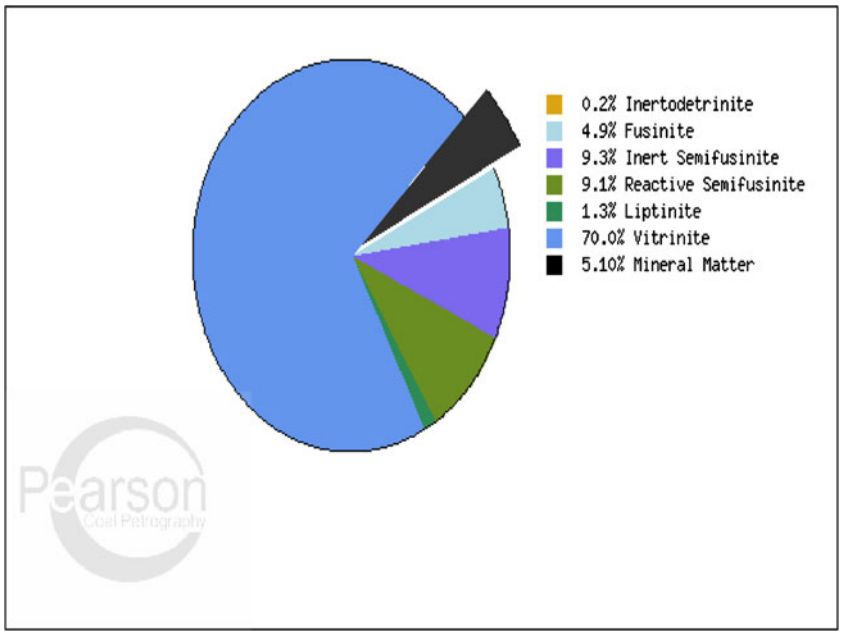


Fig. 13 Maceral pie-chart for sample MG1D (seam A)

Thermal maturity and rank of coal

The thermal maturity of the analysed samples indicated by Tmax of 419 to 431 °C, 413 to 422 °C and 426 °C for the shale, coal and coaly shale, respectively, indicates they are immature. The Tmax of the coals are generally lower than the shales and coaly shales. Sykes and Snowdon (2002) proposed that coaly source rocks are sufficiently different from

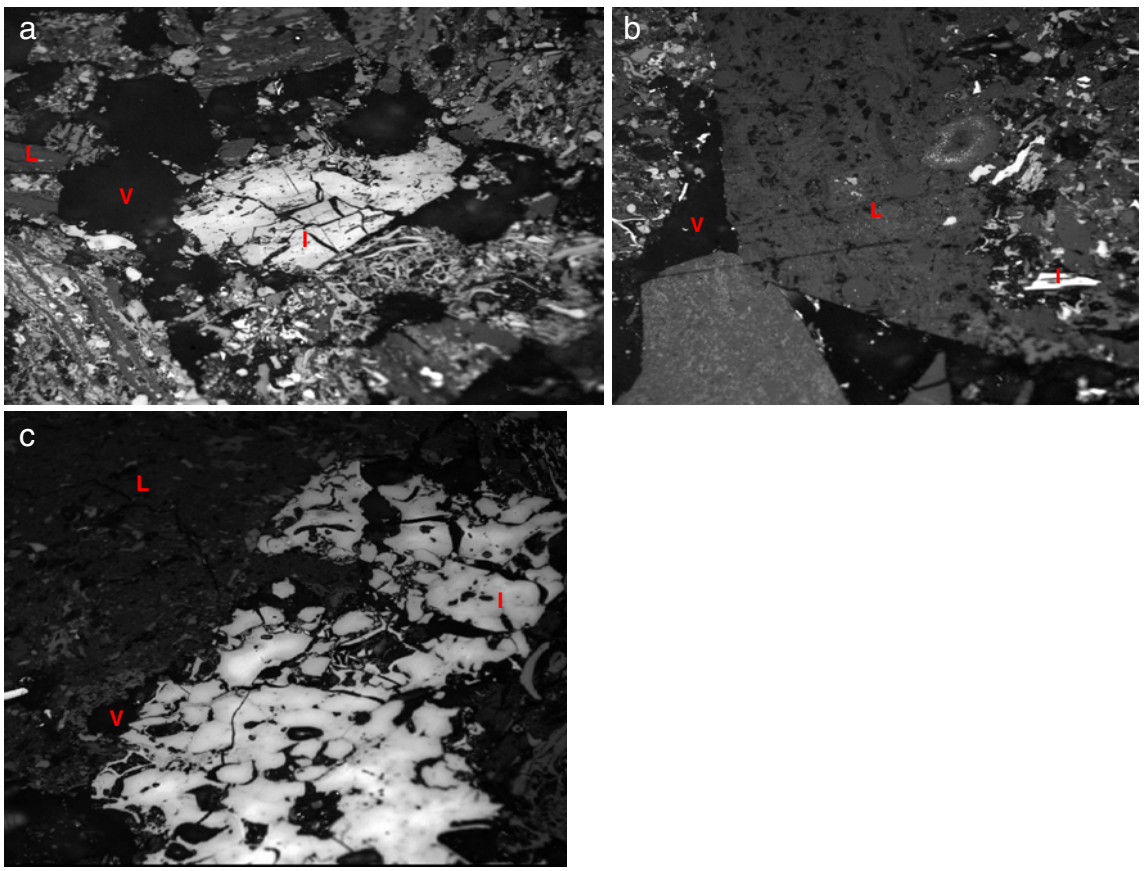


Fig. 14 **a**, **b**, **c** Showing photomicrograph of coal sample MG1D, MG1W and MG2H, respectively. Liptinite shows *greyish colouration*, vitrinite is *dark* and inertinite has *white colouration* under reflected light. *L* liptinite, *V* vitrinite, *I* inertinite

marine and lacustrine source rocks in their organic matter characteristics to warrant separate guidelines for their assessment based on Rock-Eval pyrolysis. Using data from some New Zealand coals, it was concluded that the threshold for oil generation in coals occurs at Tmax of 420 to 430 °C (Ro 0.55–0.6 %), and the threshold for oil expulsion is at Tmax 430 to 440 °C (Ro 0.65–0.85 %). However, in the coal samples analysed (MGID, MG1W and MG2H), the maximum vitrinite reflectance (Romax) values are 0.55, 0.49 and 0.48 Ro %, respectively (Table 2). The data that the investigated coals are immature to marginally mature to generate and expel oil. The plot of HI versus Tmax (Fig. 6) and HI versus VR (Fig. 7) reveals that most of the samples are immature to marginally mature for generation and expulsion of oil. The conversion of kerogen to oil or gas depends on the production index (PI) and the Tmax. The results (Table 1) show that all the samples have low value of PI (less than 0.1) which also correspond to low Tmax, indicating low level conversion (Figs. 8 and 9). The Ro value ranges from 0.48 to 0.55 Ro% indicating a coalification stage of sub-bituminous B to sub-bituminous A (Fig. 10).

Paleoenvironment

Application of macerals group in coal facies based on organic petrography has created a new trend in paleoenvironmental analysis of coal (Akande et al. 1992). Samples MG1W (seam A1) and MG2H (seam A2) have high vitrinite (59.3 and 70.1 %, respectively) (Table 2) indicating wet forest swamp facies mainly from arborescent vegetation with high clay mineral deposited in wet anoxic environment (reducing condition). In MG1D (seam B), the high value of inertinites (53 %) and increasing fusinites (9.3 %) at the bottom part of the seam indicate shift to drier condition or alteration of high and low ground water tables possibly due to periodic drainage of the peat surface. The relatively low mineral matter and high inertinite may indicate a depositional environment conducive to the oxidation of woody materials (vitrinite) under oxidizing condition or high biochemical degradation (micrinite) and lack of formation of much mineral matter. The degradation of the woody tissue could be affected by so many factors such as the type of plant, temperature of the peat, bacteria action, PH and depth of water (Teichmüller and Teichmüller 1982; Stout and Spackman 1989). Akande et al. (1992) has reported similar maceral compositions of the coals in Lower Benue Trough (Onyeama coal, Orukpa coal and Okaba coal). There is predominance of huminite (vitrinite) (44–98.2 %) and inertinite (2.3–51.5 %) in the coals with relatively low to moderate liptinite (1.8–39.8 %) and mineral matter (less than 10 %). This suggests wet forest swamp environment (Teichmüller and Teichmüller 1982; Bustin et al. 1983) with arborescent vegetation (Rimmer and Davis 1988).The pie charts and the photomicrograph of the coal samples are presented in Figs. 11, 12, 13 and 14.

Conclusion

The organic geochemical data (TOC and Rock-Eval) shows that the coal, coaly shale and shale are good to excellent source rocks in the study area. The HI and predominance of vitrinitic maceral group suggest type III kerogen sourced from terrestrial plant and capable of generating gas (biogenic). The low HI and liptinite content of the coal indicate the coals only have potential for gas.

The Tmax with the vitrinite reflectance data reveals immature to marginally mature status of the source intervals and also low level conversion of the kerogen to oil.

The lower coal seam (seam B) was probably deposited under oxic condition in the deltaic plain due to high inertinite content and low mineral matter while the upper coal seam (seam A1 and A2) were probably deposited in anoxic setting in the upper deltaic plain.

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