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Source Rock Kinetics and Organic Petrology of the Gombe Formation, Gongola Basin Nigeria: Implication for Hydrocarbon Potential

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Abstract

The interbedded coals and shales facies of the Gombe Formation were subjected to organic petrology and source rock kinetics for evaluation of thermal maturity, kerogen type and the hydrocarbon generation from the kerogen. The distribution and kinetic parameters obtained through kerogen cracking was generated by processing the data obtained from Rock eval 6 pyrolysis using ORFA (One Run Fixed A) software. The activation energy distributions observed in the samples are broad (41–65 kcal/mol) with associated fixed frequency factors of 2.00E+14/s indicating heterogeneous compositions and bond types typical of Type III kerogen (HI = 57-172 mgHC/gTOC). The peak hydrocarbon bond breaking is between 54 and 55 kcal/mol for the organofacies defining up to 70% of the petroleum potential while the main phase and peak of hydrocarbon generation is between 460 – 465°C for the organofacies at constant heating rate of 25°C/min. Petrographic examinations revealed that organic matter in the organofacies consists of opaque to non-opaque biostructured phytoclasts, cuticles and some common spores and pollen. Vitrinitic maceral was abundant in the samples indicating gas prone organic debris. Palynofacies revealed the presence of trilete spore and pollen well preserved in the samples and showed good fluorescence. The Thermal Alteration Index (TAI) ranges from 2.4-2.6 suggesting late diagenetic stage for the organic matter maturation. It is concluded that the samples are thermally immature and constitute moderate to good quantity of organic matter with potential to generate mainly gaseous hydrocarbon.

Keywords*: Kinetics; Kerogen; Palynofacies; Phytoclast; Maceral.*

1. Introduction

The Gongola sub basin in the Northern Benue Trough is an inland sedimentary basin in the northeastern Nigeria (Figure 1). The investigated Maastrichtian source rock facies were exposed at Maiganga village in Kumo town near Gombe State. The coal mine at Maiganga village is an open pit consisting of different lithologies such as coals, shales, siltstones, sandstones, and ironstones. Some workers have carried out sedimentological and geochemical investigations on outcrop and borehole samples in the Gongola and Yola-arm of the Northern Benue Trough. The Cretaceous Gongola sub basin is a north - south trending arm of the Northern Benue Trough was formed by rifting processes during the opening of the South Atlantic and the separation of South American and African plate in the Mesozoic [1-2]. The stratigraphic unit (Figure 2) from the base consists of the basement rock followed by the Albian-Cenomanian sandstone of Bima Formation. The sandstones, shales, and limestones of the Yolde Formation (continental-marine) succeeded the Bima Formation. Overlying the Yolde Formation is the late Turonian-Coniacian fossiliferous limestones and shales of Pindiga Formation. This formation is succeeded by the Maastrichtian Gombe Formation consisting of sandstones, shales, siltstones, mudstones, and coals. The Paleogene Kerri Kerri Formation is the youngest formation consisting of sandstone and alluvial deposit [3].

Hydrocarbon prospectivity and research is still active in the northern Benue Trough of Nigeria. Several workers [4-7] have carried out organic geochemical screening on coals and interbedded shales of Gombe Formation using TOC and Rock Eval Pyrolysis to investigate for hydrocarbon prospectivity. The the organofacies were interpreted to be gas prone based on the geochemical screening. Further studies on the organofacies of Gombe Formation by [4,8] have confirmed Type III kerogen and gaseous hydrocarbon generation at low thermal maturation in the early stages.

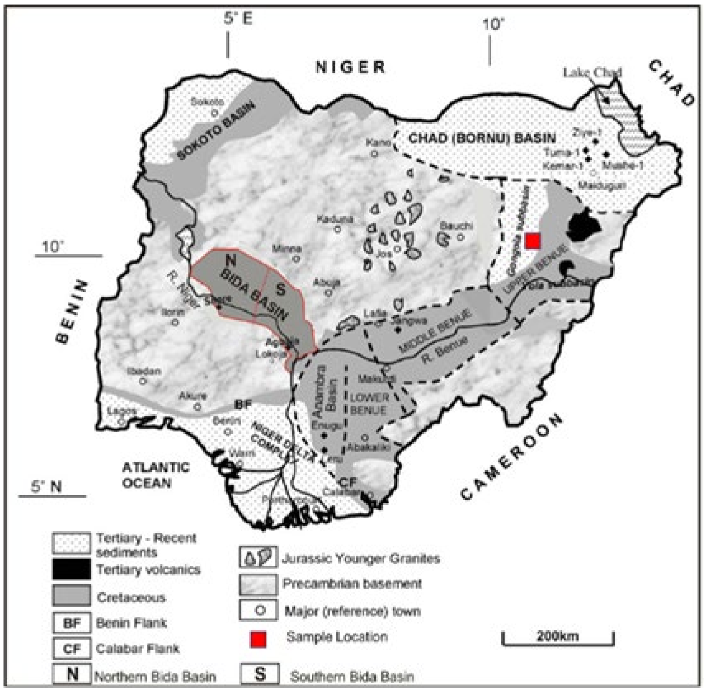


Fig. 1. Geological map of Nigeria showing the sedimentary basins and the study location (modified after [6])

However, the recent discovery of hydrocarbon (oil, gas, and condensates) in the Kolmani River (specifically Kolmani I and Kolmani II well) within the boundary of Bauchi and Gombe States in the northeastern part of Nigeria has necessitated further studies to look at the possibility of the coaly source rocks of Gombe Formation to generate liquid hydrocarbon. The biomarker characterization of the shales and coaly source rocks by [8] led credence to the fact that the organofacies of Gombe Formation has the potential to generate liquid hydrocarbon at higher thermal maturity due to it long chain aliphatics. In view of this development, further studies on the samples needed to be carried out using different approach from the previous studies. In this paper, the hydrocarbon generation potential of the coal and shaly source rocks were characterized using bulk kinetics and organic petrology with the view of evaluating the hydrocarbon generation potential of the basin. The objective of this study is to determine hydrocarbon generation, kerogen type, source of the organic matter and maturity of the organic facies of Gombe Formation.

Age	Formation (Gongola Basin)	Lithology	Paleoenvironment
Paleogene	Kerri-Kerri	Sandstone Conglomerate	Continental (Fluvial/Lacustrine)
Maastrichtian	Gombe	Sandstone, Coal, Shale, Siltstone, Claystone	Fluvial/Deltaic-Open marine
Campanian			
Santonian			
Coniacian	Pindiga	Shale, Limestone	Marine (Estuarine)
Turonian			
Cenomanian	Yolde	Sandstone, Shale, Siltstone	Deltaic-Barrier island
Albian	Bima	Sandstone	Continental (Braided/Lacustrine/Alluvial)
Precambrian	Basement Complex	Granite/Gneiss/Migmatite/Schist	Igneous/Metamorphic

- - Unconformity (Para) —— Unconformity (Non)

Fig. 2. Stratigraphy of northernBenue Trough (modified after [9])

2. Methodology

The method employed in this study involves the field work and laboratory analyses. Twenty-six samples were obtained through sampling from two sections of the mine while three borehole samples were collected from a borehole. The sections were logged from the base to the top and show an intercalation of shale with the coal seams (Figures 3, 4 and 5). The organic source richness were determined by the Total Organic Carbon and hydrocarbon potential [4,8]. Nine (9) samples were investigated by Organic Petrology (visual kerogen and maceral analysis) for determination of kerogen quality, maturity, and hydrocarbon potential. All the analyses were carried out at Stratochem Laboratory Services in Egypt.

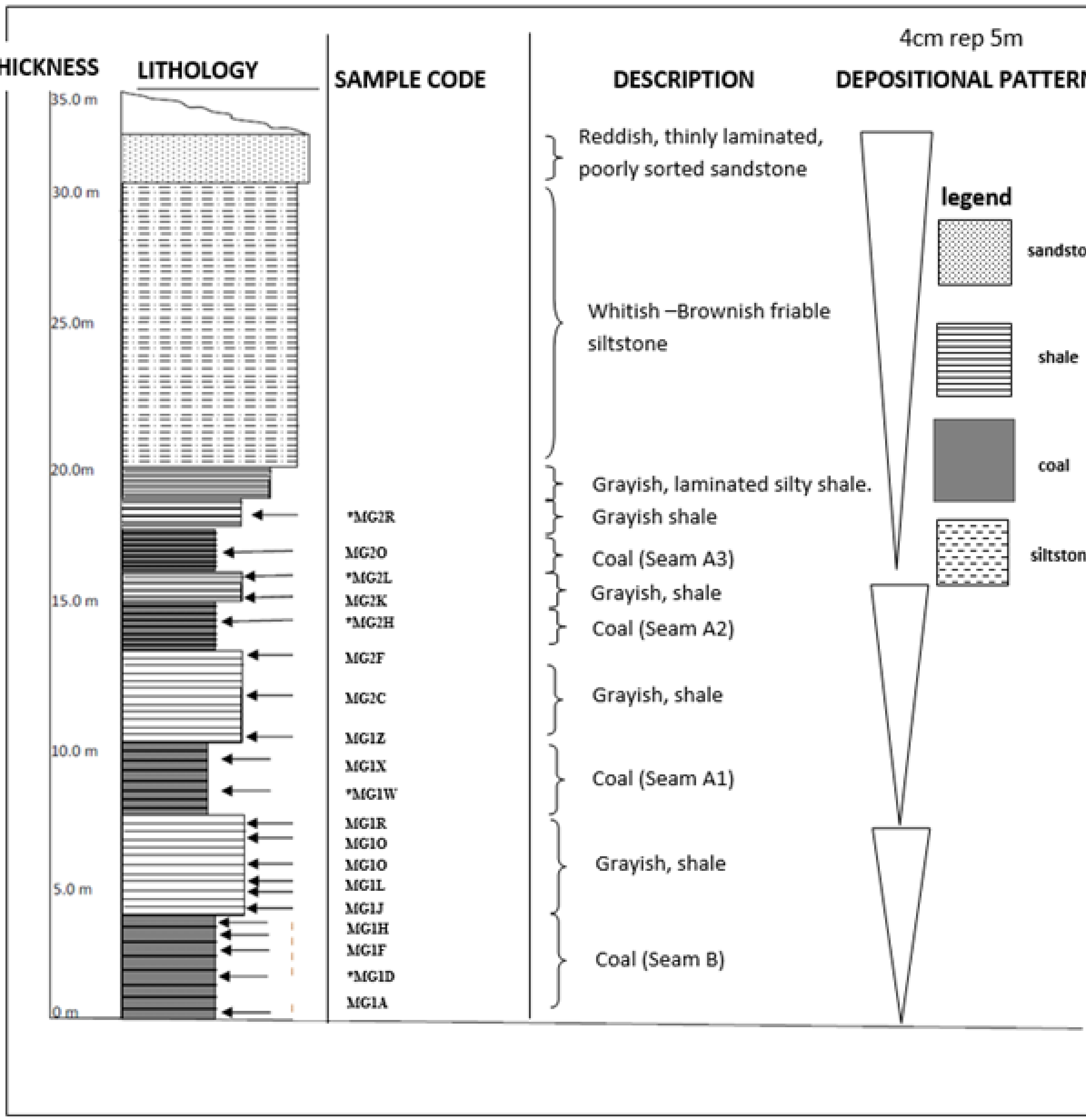


Fig. 3. Lithologic succession of Gombe Formation at the Maiganga mine (Phase I). The succession coarsens upward from coal, shale, siltstone to sandstone. Sample codes with star symbol indicates the selected and analyzed samples (modified after [4,8]). Coordinates- (10^0 02′ 39″ N, 11^0 12′ 17″ E)

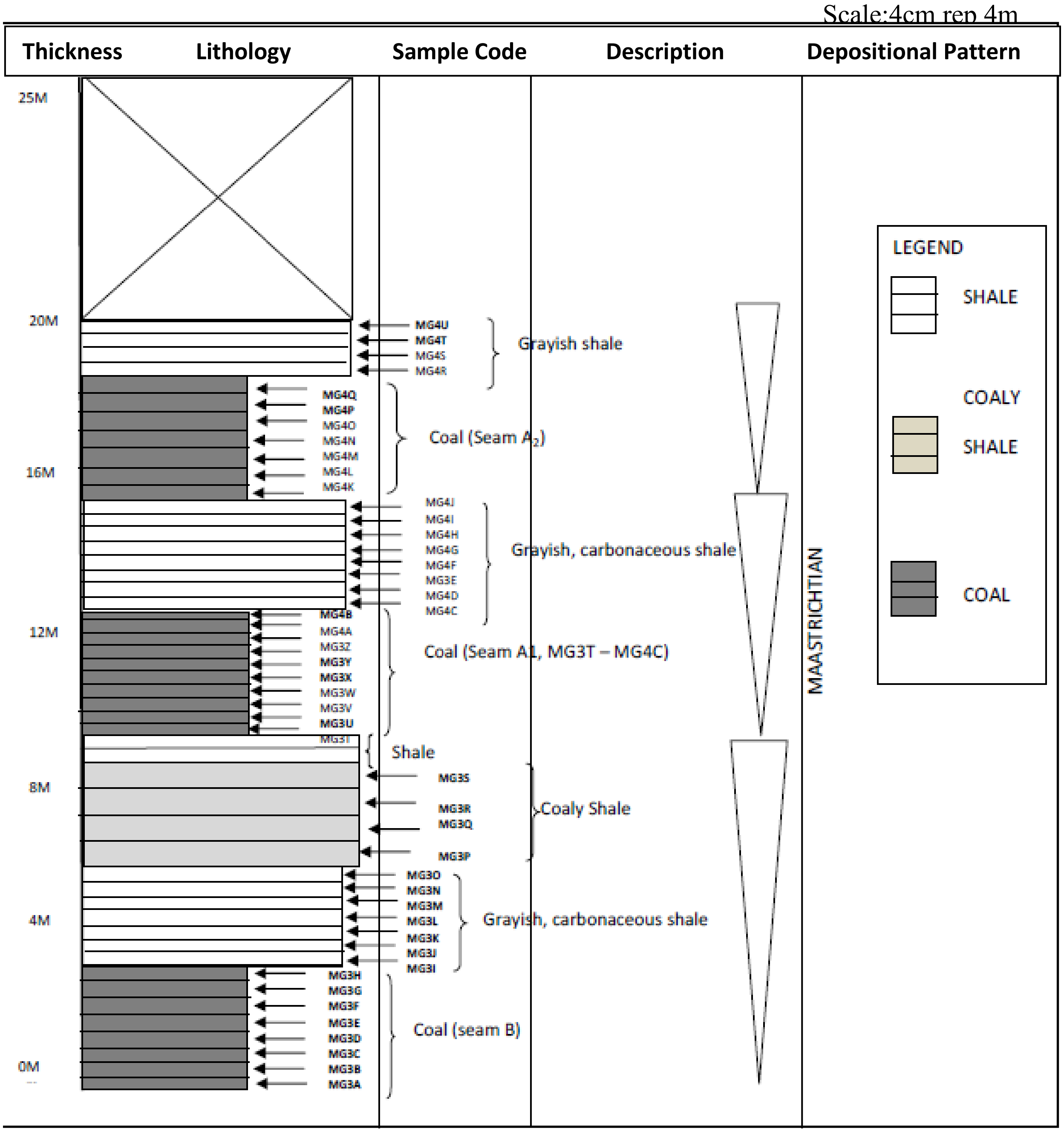


Fig. 4. Lithologic succession of Gombe Formation at Maiganga mine (Phase II). The succession coarsens upward from coal, shale, coaly shale. Sample codes with star symbol indicates the selected and analyzed samples (modified after [4,8]). Coordinates- (10^0 04′ 46″ N, 11^0 12′ 23″ E)

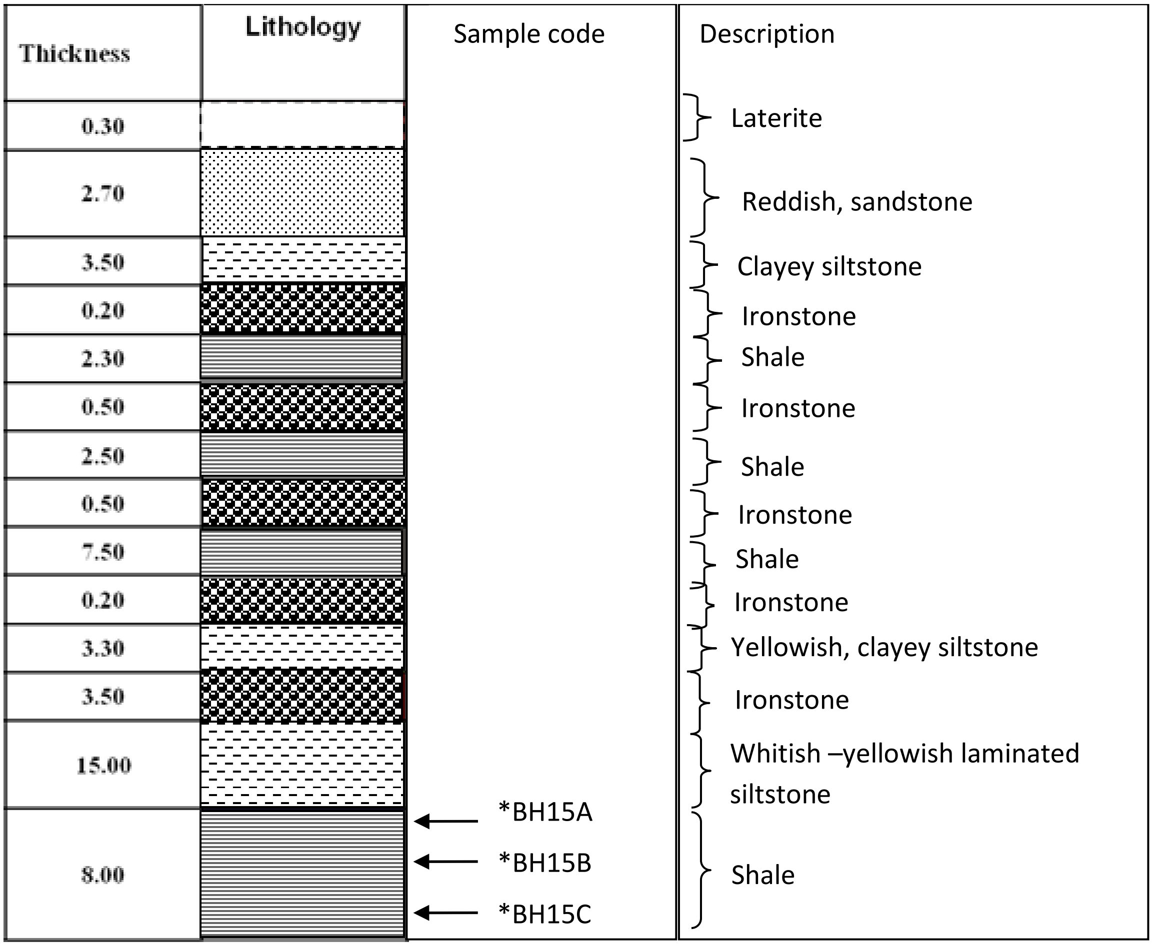


Fig. 5. Litholog of Borehole sampled at Maiganga. GPS: x = 734251, y = 1105749, z = 458. The log shows shale, siltstone, and ironstone intercalation. Sample codes with star symbol indicates selected and analyzed samples (modified after [4,8])

The pyrolysis was carried out by heating the samples in the absence of oxygen in RE-6 machine. Each sample already pre-cleaned was crushed in mortal using pestle and (100 mg) weighed into a sample holder. The samples were poured into the RE-6 crucible using a funnel and capped. The crucible was placed in the RE-6 Carousel and the samples analyzed according to the instrument manual. Each sample is transferred into the furnace where it was heated initially at 300°C for three minutes in an atmosphere of helium to release the free hydrocarbons (S_1). The S_2 gives the hydrocarbon generated by thermal cracking of the kerogen immediately as the oven temperature was increased rapidly to 550°C at the rate of 25°C/min. After the pyrolysis, the results of the Rock Eval Pyrolysis for eight (8) samples (coals and shales) were analyzed by One Run fix A (ORFA) software for the bulk kinetics to determine the hydrocarbon generation potential of the kerogen (Table 1). The samples selected for the kinetics were based on the TOC and S_2 threshold values.

The kerogen samples were studied under the microscope. Sample preparation was done by cleaning 20-40g of each sample to remove any contamination and impurities and then crushed to fragments to pass through a 40-mesh sieve. The crushed samples were first treated with hydrochloric acid to remove carbonates and hydrofluoric acid to remove silicates minerals. A heavy liquid ($ZnCl_2$) was added to concentrate the kerogen. After decantation, the organic residue was sieved at 10μm (micron mesh) sieve, and the retained strew was mounted on glass slide for kerogen and fluorescence studies using fluorescence and transmitted microscopy. Each slide was examined under incident blue light fluorescence using a Zeiss Axio-

A1 Scope at X50 magnification. The essence was to determine the preservation state of palynomorphs, and amorphous organic matter present based on the fluorescence preservation of [10]. The coal macerals were examined under reflected light microscope. The polished specimens were made from crushed 1 mm size samples mounted in epoxy resin. Maceral observation was done by using Leitz MPV-2 photomicroscope. The composition of each maceral was determined by a swift automatic point counter based on at least 500 counts. The preparation and polishing of the specimens were carried out in accordance with [11].

3. Results and discussion

The results of the bulk kinetics, visual kerogen analyses and maceral data are presented in Tables 1, 2 and 3.

Table 1. Bulk Kinetics data for Coal and Shale Samples of Maiganga, Gombe Formation

S/N	S. code	Lithology	Sample type	Depth (m)	TOC	S1	S2	Tmax (oC)	HI	Ea Range	Mean (Ea)	Oil (%)
1	MG3D	Coal	Surface	23	53.40	0.49	30.58	429	57	41-65	57.64	64
2	MG3S	C. shale	Surface	17	7.90	0.26	11.03	428	140	41-65	56.19	70.8
3	MG3Z	Coal	Surface	12	55.80	0.97	73.15	435	131	41-65	57.35	70.3
4	MG4D	Shale	Surface	13	4.64	0.09	4.84	428	104	41-65	56.61	68.6
5	MG4K	Coal	Surface	9	32.40	0.67	55.29	439	171	41-65	57.49	72.3
6	BH15A	Shale	Core	44	1.95	0.16	2.97	428	152	41-65	56.17	71.5
7	BH15B	Shale	Core	46	2.96	0.09	5.09	428	172	41-65	56.66	72.4
8	BH15C	Shale	Core	48	4.84	0.09	6.89	427	142	41-65	56.85	70.9

TOC= Total organic carbon, S1=Volatile hydrocarbon which are mainly stripped at temperatures about 300oC (mgHC/g rock). S2= Hydrocarbons generated through thermal cracking of kerogen at temperatures in the range of 300-650oC. Tmax = Temperature of maximum generation of S2 peak (mg HC/g rock). HI= (Hydrogen index) mg HC/g TOC,Ea= Activation energy

Table 2. Visual Kerogen, Thermal Alteration Index and Vitrinite reflectance data of Coal and Shale samples of Maiganga, Gombe Formation

Sample code	Lithology	Alginite (%)	Liptinite (%)	Amorphous (%)	Vitrinite (%)	Inertinite (%)	Fluorescence	% Oil prone	% Gas Prone	TAI	VR	Spore Colour
MG2L	Shale	0	40	0	35	25	Good	40	35	2.4-2.5	0.49	Pale yellow-yellow
MG2R	Shale	0	30	0	35	35	Good	30	35	2.5-2.6	0.50	Yellow-Orange
MG3D	Coal	0	5	0	50	45	Good	5	50	2.5-2.6	0.50	Orange
MG3Z	Coal	0	5	0	55	40	Good	5	55	2.4-2.5	0.46	Pale yellow-yellow
MG4D	Shale	0	30	0	45	25	Good	30	45	2.5-2.6	0.53	Orange
BH15A	Shale	0	40	0	35	25	Good	40	35	2.5-2.6	0.50	Dark Orange

TAI- Thermal Alteration index, VR- Vitrinite Reflectance

Table 3. Maceral and vitrinite reflectance data for Coal samples of Maiganga, Gombe Formation

code	Lithology	Romax	R.R	Reactive components (%)				Inert components (%)			m.m
		(%)	(%)	liptinite	vitrinite	R.semi-fusinite	I. semi-fusinite	fusinite	Inertodetrinite	Inertinite (%)	(%)
MG2H	Coal	0.48	0.45	1.3	70.1	9.1	9.3	4.9	0.2	23.5	5.1
MG1W	Coal	0.49	0.46	1.9	59.3	13.9	13.9	5.9	0.2	33.9	4.9
MG1D	Coal	0.55	0.52	0.4	41.4	21.9	21.9	9.3	0.2	53.3	4.9

Romax: Maximum vitrinite reflectance, R.R: Random reflectance, m.m: mineral matter

3.1. Organic source richness, hydrocarbon potential and kerogen type

The average TOC values of the samples analyzed exceeded the minimal 0.5 wt%, 0.3% and 1% required for a shale, carbonate, and clastic source rocks respectively [12] and thus indicate good source potential. The hydrocarbon generation potential of the shales and coaly source rocks of Gombe Formation investigated by TOC and Rock eval Pyrolysis were reported by [4,8] indicating Type III kerogen while the maturity level of the organic matter is at the onset of hydrocarbon generation.

3.2. Bulk kinetics

Kerogen classification or organic matter typing is a function of the total hydrocarbon generation potential, kinetics, and oil chemistry [13-15]. The distribution of the kinetic parameters, activation energy and hydrocarbon percentage are shown in (Table 1).

3.3. Activation energy and hydrocarbon potential

Generally, the activation energy distributions observed in the samples are broad which implies heterogeneous compositions, typical of terrigenous materials derived from higher land plants [16]. The activation energies (Ea) of the samples range from 41–65 kcal/mol, with a fixed frequency factors of 2.00E+14/s. The coal facies are comparatively slightly matured than the shale facies and showed chemical bonds with activation energies between (41-65 kcal/mol) with mean Ea of 57.49 kcal/mol. The peak energy for the hydrocarbon bond is at 55 kcal/mol. The shale facies also have broad activation energies from (41-65kcal/mol) having mean Ea of 56.57 kcal/mol.

The distribution in both facies is indicative of heterogeneous compositions and bond types indicate Type III organic matter. The coal and shale facies are in early- late mature oil and gas generating stages which probably have experienced a partial conversion of kerogen to oil or gas as depicted by the broad range of activation energy. The major phase and peak of hydrocarbon generation range between 460 – 465^{o}C for the coal and shale facies at constant heating rate of 25^{o}C/min. The Pyrograms (reaction rate vs temperature) showed the calculated and measured hydrocarbon generation rate for coal and shale samples of Maiganga (Figure 6a-h). The bar height from each activation energy signifies the generation potential for each sample (Figure 7a-h) with peak hydrocarbon bond breaking at 54 and 55 kcal/mol defining up to 70% of the petroleum potential. At this stage, most of the kerogen has been converted to oil. The percentage of oil generated from the HIs for the coal facies range from (64-72%) while the shale facies range from (68.6-72.4%) (Table 1).

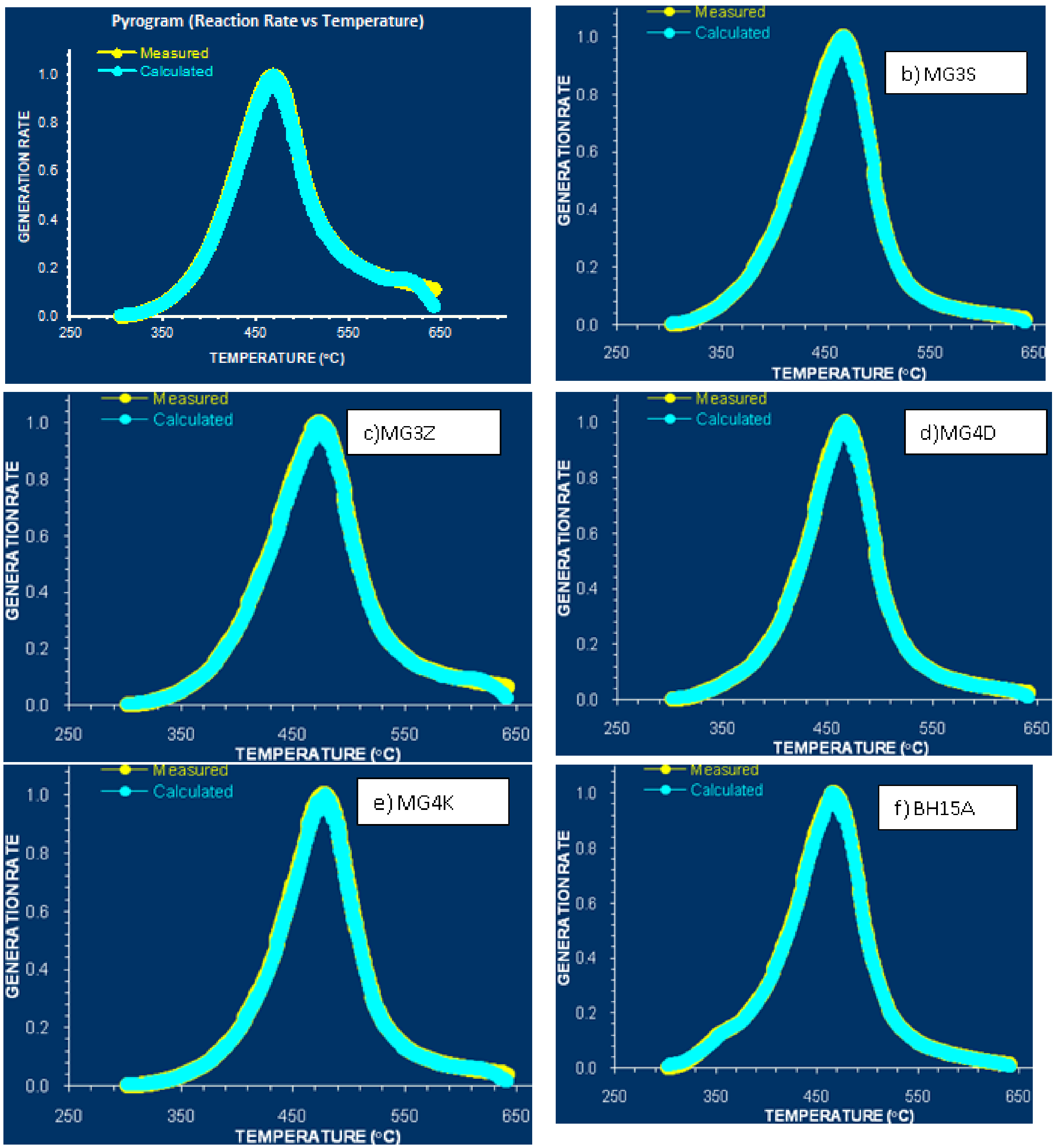
3.4. Organic petrology

Visual kerogen analyses of the shales and maceral studies for the coal samples were carried out to deduce the maceral composition, maturity of the organic matter and hydrocarbon generation potential of the source beds. The results of the petrographic analyses are presented in Table 2 and 3.

3.5. Maceral composition and hydrocarbon potential

The petrology of organic matter is a function of several parameters which includes the thermal maturity of the organic constituents and the macerals composition [17]. The vitrinite is dark under reflected light; liptinite is gray while inertinite is white. Petrographic examination revealed that organic matter in the coal and shale samples consist of opaque to non-opaque biostructure phytoclasts and cuticles associated with common amounts of spores and pollen (Figure 8-13).

The types of petroleum generated from coaly source rocks are dependent on the availability of hydrogen [12,18]. The potentiality of coal to generate liquid hydrocarbon is subject to availability of liptinite maceral [19].[20] proposed 10% hydrogen rich maceral while [21] suggest 15-20% liptinite to generate oil in coaly source rocks. Vitrinite is the most abundant and dominant maceral in the samples. it ranges in the coals from 41.4%-70.1% while for the shale, it ranges from 35%-45% (Table 2 and Table 3). The vitrinite is dark; the liptinite is gray while the inertinite is white under reflected light (Figure 14). The inertinite content ranges from 25%-35% for the shale while the coal ranges from 23.5%-45% (Table 2 and Table 3). As indicated from (Table 2), the percentage oil prone for the shale is about 30-40% with respect to the liptinite content. The liptinite contents of the is low (5%) indicating that the potential to generate liquid hydrocarbon is minimal.



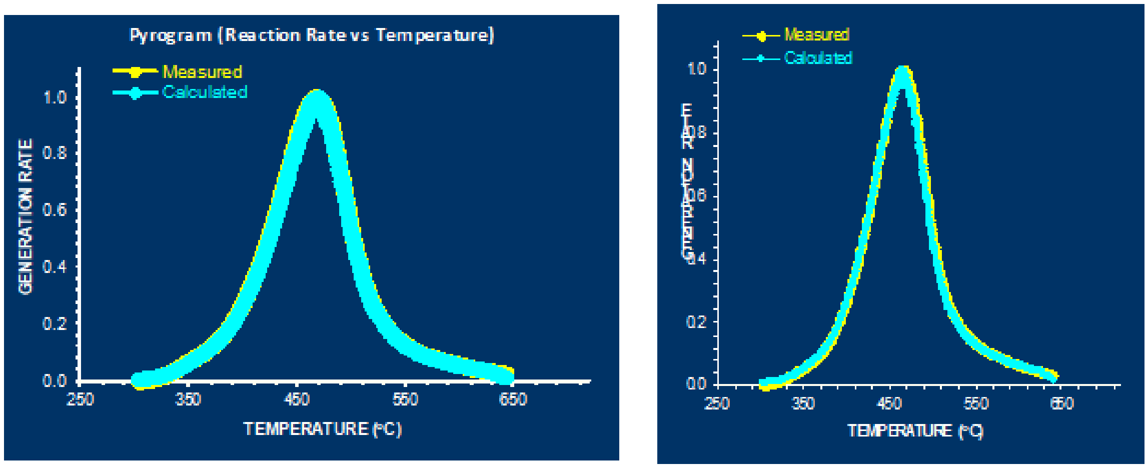
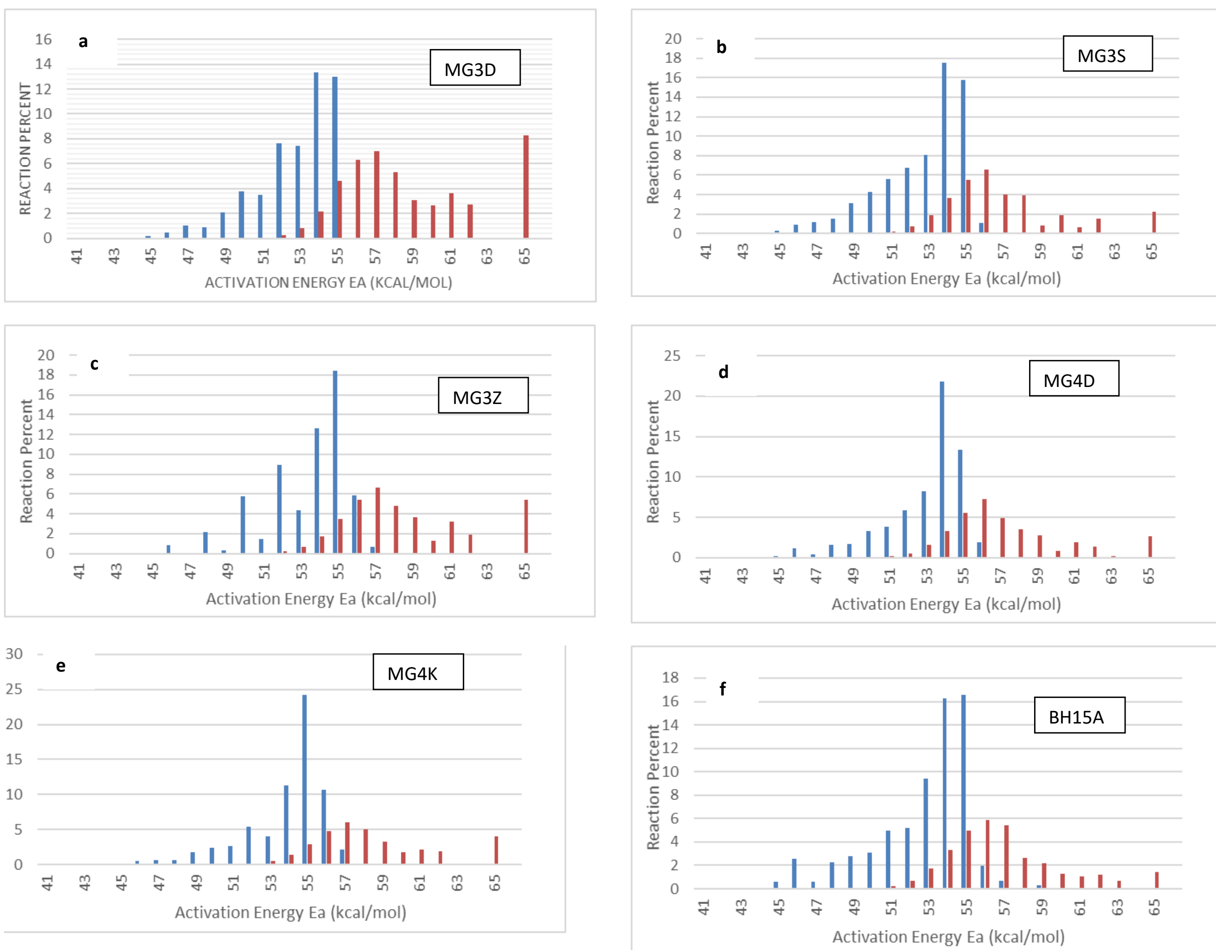


Fig. 6 (a-h). Pyrogram (reaction rate vs temperature) showing calculated and measured hydrocarbon generation rate for coal and shale samples of Maiganga (Note: peak of hydrocarbon generation for the samples is between 460 – 465°C



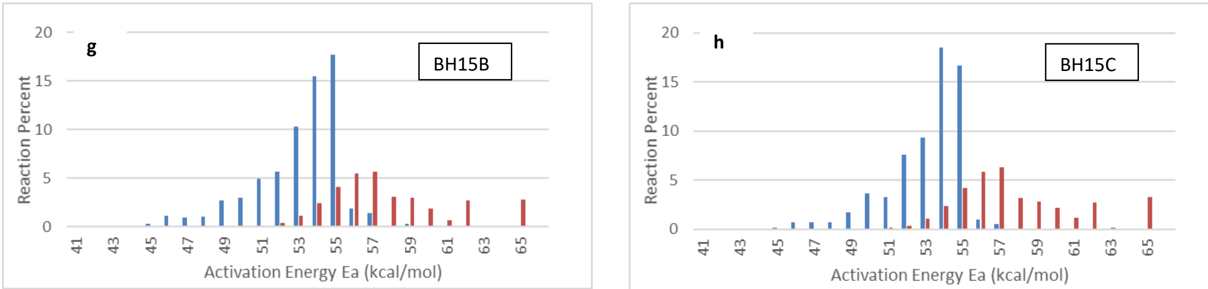
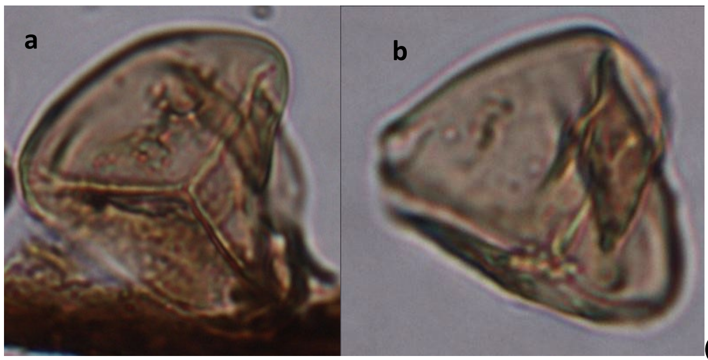


Fig. 7(a-h). Bar charts indicate the percentage reaction vs activation energy for coal and shale samples of Gombe Formation. Note: Oil (Blue) and Gas (Red) Kinetics. Peak hydrocarbon generation is at 55 (Ea) for most of the samples



(x 400)

Fig. 8. Photomicrographs of Palynomorphs in sample MG2L (Organic matter in this sample consists predominantly of large non-opaque biostructured phytoclasts and cuticles associated with very common amounts of pollen and spores (trilete spore). (a-*Gleicheneites* sp. b- *Cyathidites* sp.)

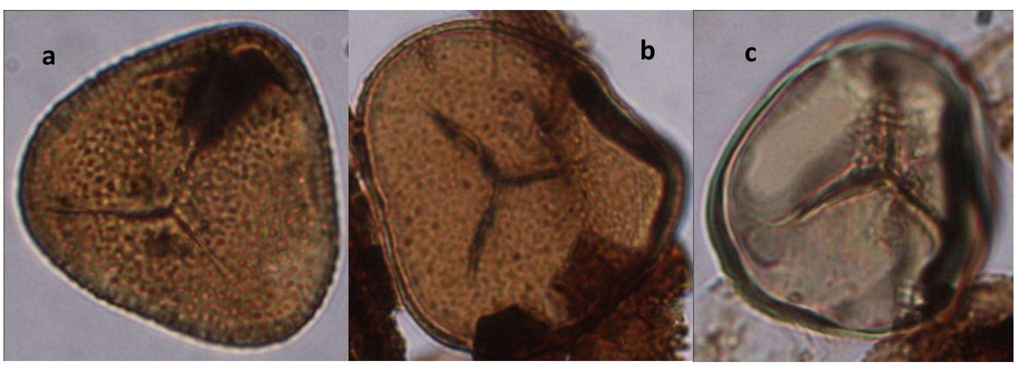


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Fig. 9. Photomicrographs of Palynomorphs in sample MG2R (Organic matter in this sample consists of predominant amount of phytoclasts (biostructured and cuticles) associated with commonamounts of pollen and spores. (a-*Foveotriletes margaritae*, b-*Rugulatisporites caperatus* c – *Cyathidites* sp.)

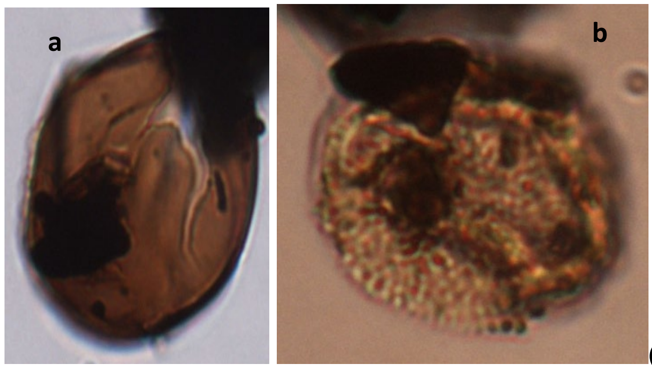

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Fig. 10. Photomicrographs of Palynomorphs in sample MG3D (Organic matter in this sample consists predominantly of opaque phytoclasts and rare amount of biostructured phytoclasts associated with rare amount of pollen grains. (a - *Protoperidinium* b- *Proxapertites* sp.)

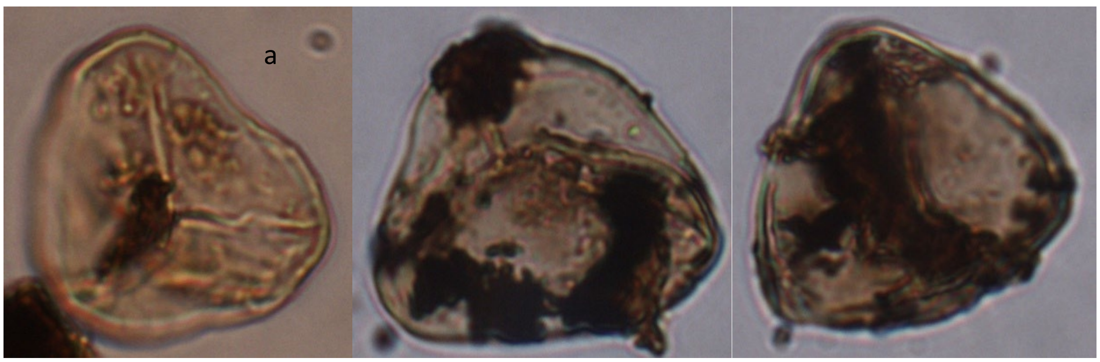

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Fig. 11. Photomicrographs of Palynomorphs in sample MG3Z (Organic matter in this sample consists of very common amount of opaque phytoclasts associated with rare amounts of biostructured phytoclasts and spores. a- *Elaeis guineensis*

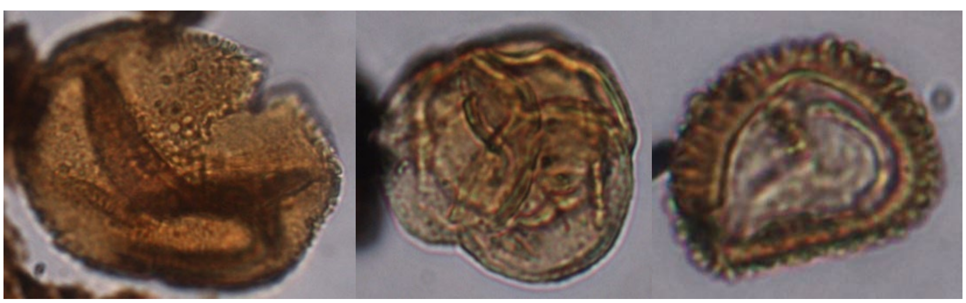

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Fig. 12. Photomicrographs of Palynomorphs in sample MG4D (Organic matter in this sample consists predominantly of biostructured phytoclasts and cuticles associated with a common amount of sporomorphs.

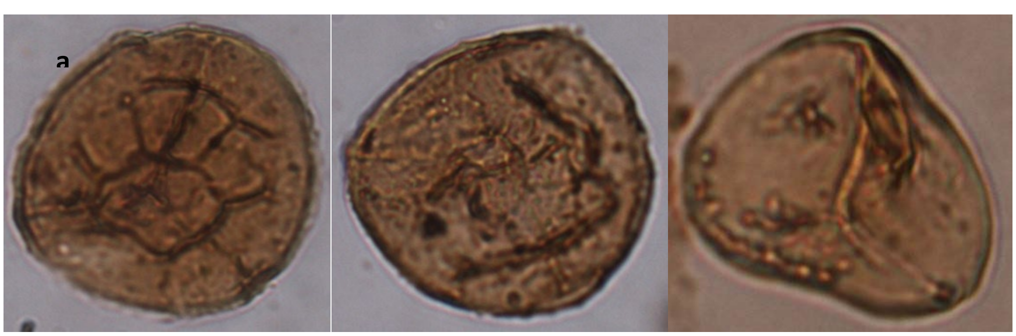

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Fig. 13. Photomicrographs of Palynomorph in sample BH15A (Organic matter in this sample consists predominantly of biostructured phytoclasts associated with common amounts of spores and pollen, and a moderate number of cuticles. (a-*Zlivisporeites blanensis*).

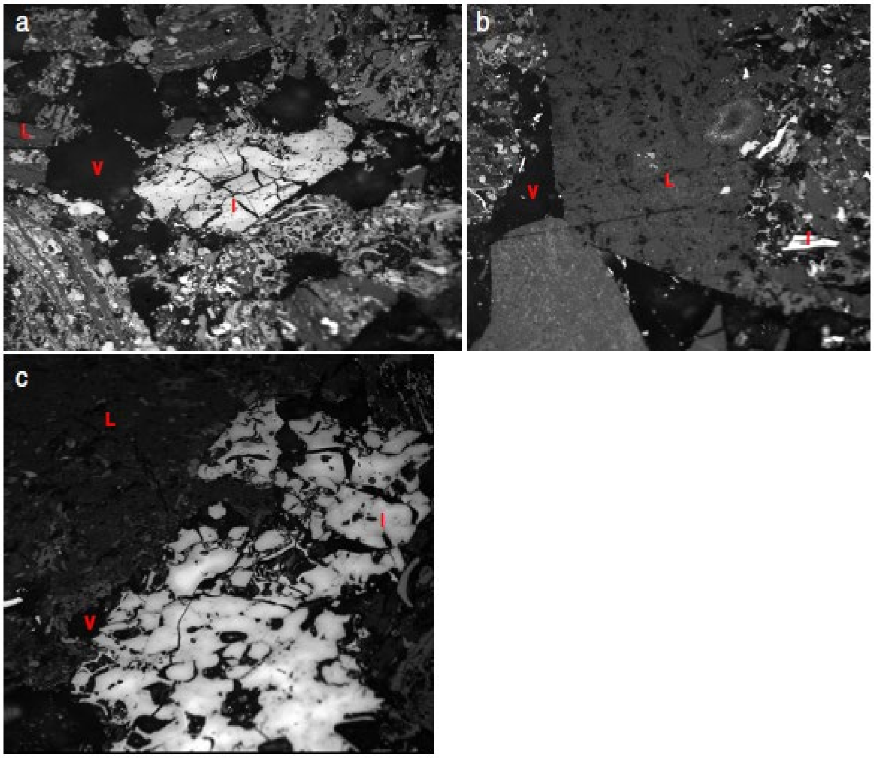

Fig. 14. Photomicrograph of coal sample a) MG1D, b) MG1W and c) MG2H. (Liptinite shows grayish coloration, vitrinite is dark and inertinite has white under reflected light. V: vitrinite, L: liptinite, I: inertinite

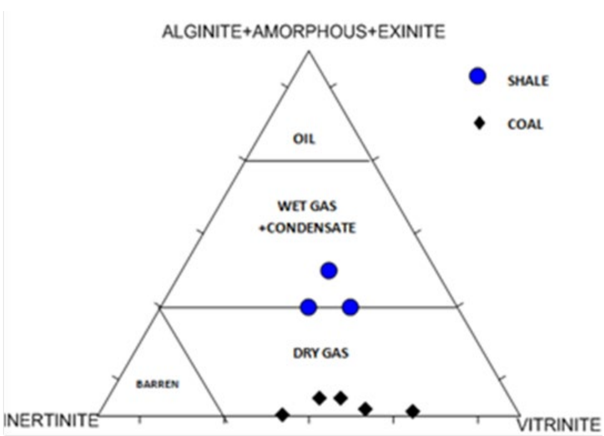

Fig. 15. Visual kerogen analyses of the samples compared with the reference diagram of Tissot and Welte (1978) indicates that the coal and shales are gas prone

[18] has proven that humic coals dominated by huminite can generate oil. Liptinite macerals are more paraffinic in structure and are oil prone than huminite due to the long aliphatic in the coal structure component in the range of (>C_{20}-C_{25}) [22]. Since vitrinite is the most abundant maceral in the coal samples analyzed, the coal samples have the potential to generate hydrocarbon gas (dry gas). As indicated by the ternary plot in (Figure 15), the shale has the potential to generate wet gas. The high percentage of the vitrinite indicates gas prone and the organic matter deposited in proximity to the source. The high percentages of the gas prone kerogen and their low corresponding hydrogen index (HI) may be due to pre- depositional or post depositional oxidation from the bulk of the sediments in the stratigraphic section or reworking of the organics.

3.6. Thermal maturity

Petrographic examination revealed that organic matter in the coal and shale samples consists of opaque to non-opaque biostructured phytoclasts and cuticles associated with common amounts of spores and pollen (Figure 8-13). Palynofacies study indicates the presence of trilete spore and pollen well preserved in all the samples and showed yellow-orange fluorescence (Figure 8-13). The vitrinite reflectance (Ro) of the coal ranges from 0.46-0.55 and 0.49-0.53 for the shale (Table 2 and Table 3). These values indicate immature to marginal maturity for the source beds. The thermal maturity (T_{max}) for hydrocarbon generation for most source rock is between 430^oC - 435^oC corresponding to 0.70-0.81Ro whereas T_{max} for Type (I and II) and Type III kerogen oil window is between 430^oC-470^oC and 465^oC-470^oC respectively [23]. Most humic coals generate hydrocarbons at 0.50-0.60Ro and expel at 0.65Ro [23]. The maturity of the samples suggests that the organic matter has not reached the generation stage of thermal maturity for oil prone kerogen. The thermal alteration index value between 2.4-2.6 (chevron scale) (Table 2) further corroborates late diagenetic stage for the organic matter maturation as supported by the spore coloration of yellow to orange.

4. Conclusion

The following findings were observed based on the result of the bulk kinetics and the organic petrography.

1. The bulk kinetics data indicated terrigenous organic matter derived from higher land plants as evidenced from heterogenous composition and broad activation energies.
2. The major phase and peak of hydrocarbon generation ranged between 460 – 465^oC for the coal and shale facies with peak hydrocarbon bond breaking at 54 and 55 kcal/mol suggesting 70% of hydrocarbon generation from source rock kinetics.
3. Vitrinite maceral dominate the coal samples with potential to generate gaseous hydrocarbon (dry gas) while the shale has potential to generate wet gas.
4. Visual kerogen study of the samples indicated percentage oil prone for the shale is between 30-40% with respect to the liptinite content. while the coals have low liptinite of about (5%) suggesting low potential for liquid hydrocarbon generation.
5. The vitrinite reflectance (Ro) of the coal ranged from 0.46-0.55Ro and 0.49-0.53Ro for the shale suggesting immature to marginal maturity for the source beds. This is corroborated by the thermal alteration index (TAI) value of 2.4-2.6 (chevron scale) and yellow - orange spore coloration suggesting late diagenetic stage for the organic matter maturation.
6. Palynofacies study revealed presence of trilete spores with opaque to non-opaque phytoclasts in the samples.

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