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# Pyrolysis analysis and organic petrography of Cretaceous coals of Northern Benue Trough, northeast Nigeria: Implication for oil-gas generative potential

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**Abstract**

Pyrolysis Analysis (Rock-Eval pyrolysis and total organic carbon or TOC content determination) and Organic Petrological (vitrinite reflectance and macerals identification) Analyses were conducted on Maiganga and Lamza coals from The Northern Benue Trough, Northeastern Nigeria. This with an objective of determining the kerogen types, thermal maturation and oil-gas generative potential. The study revealed that the analysed Maiganga coals are immature to mature with major gas source rock potential (pre–oil generation window) while samples from Lamza area are at early-mature to peak oil window maturity with predominantly gas generative potential. The Maiganga and Lamza coals samples have fairly mixed Type II-III and Type III kerogens and could be expected to generate major gas and limited components of liquid hydrocarbons. This study therefore, suggest that the Maiganga and Lamza coals possess qualities and can serve as good source rocks for Upper Crectaceous petroleum system of the Northern Benue Trough with major gas and minor oil generating potentials. This research however, could be used as a guide for current frontier basins exploration in the Northern Benue Trough of Nigeria for future economic growth of Nigeria.

**Keywords:** Kerogen; Pyrolysis, Petrology; Maiganga; Lamza; Northern Benue Trough

## Introduction

Coal have long been recognised as a source of gas, primarily methane and carbon dioxide, but its importance as a generator for oil is difficult to prove. However, it is now known to be a significant potential source of liquid hydrocarbons in several basins in the world (Hunt, 1991). Traditionally, coal petrographic studies mainly are used for determining coal quality, maceral compositions, paleodepositional environment, and coal rank (vitrinite-%Ro) where coals are being assessed for their petroleum-generative potential, an organic petrology approach is most informative, whereby macerals are studied in relation to diagenetic and mineral matter and solid to soluble petroleum (bitumens, crude oils) (Hunt, 1991; Abdullah, 1999).

The recognition that coal is a contributor to oil accumulation has come from a range of geochemical techniques, which incorporate to coal petrography analysis such as Rock-Eval pyrolysis, solvent extract-gas chromatography-mass spectrometry (biomarkers), open system pyrolysis gas chromatography and hydrous pyrolysis (Abdullah, 1999; 2003). The study area falls within the Northern Benue Trough of Nigeria (Fig. 1). Coal beds are present in the Northern Benue Trough in the Cretaceous sequences of Gombe Formation (Gongola Sub-basin) and Lamja Formation (Yola Sub-basin) (Obaje et al., 1994; 2004; 2006).

Previous exploration activities in the Northern Benue Trough recorded success for gas generation potential (an estimated reserve of 33 bcf) in the Kolmani River-1 well drilled by Shell Nigeria Exploration and Production Company (SNEPCO) in 1999. Since then, there has been increasing interest to search for hydrocarbons in the area. The trough consists of two major petroleum systems; the Early Cretaceous petroleum system and the Upper Cretaceous petroleum system (Abubakar, 2014; Sarki Yandoka et al., 2016). As the world's hydrocarbon reserves keep falling, alternative sources have to be explored. This leads to a sustained interest in investigating the source rock potential coaly sediments in Nigerian sedimentary basins.

This study reports the results of an investigation on the coals from two areas (Lamza and Maiganga) of the Northern Benue Trough, Northeastern Nigeria. This is with the aim of describing the organic petrography (maceral compositions), determining random vitrinite reflectance in oil (vitrinite reflectance %Ro; and coal rank), Rock-Eval pyrolysis properties (Tmax, total organic carbon, and generated-hydrocarbons potential). The study is also important due to current frontier exploration campaign and resource assessment of the entire Benue Trough for future economic growth of the country.

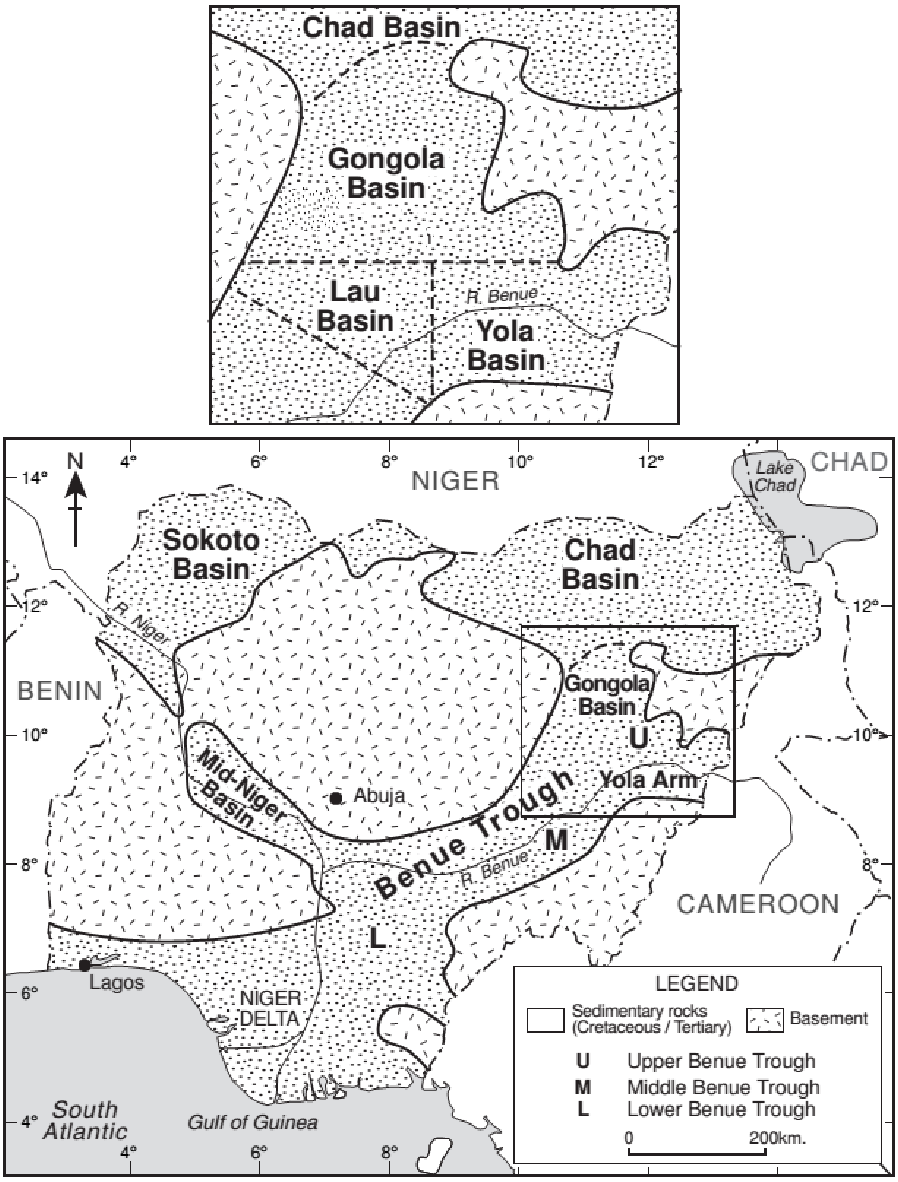


**Figure 1:** Geological map of Nigeria showing the location of the Gongola and Yola Sub-basins (after Abubakar et al., 2008)

***Geological setting***

The Benue Trough is an intra-continental Cretaceous sedimentary basin in Nigeria. It has up to 6000 m of Cretaceous–Palaeogene sediments of which those before the Mid-Santonian were folded, faulted and uplifted in several places (e.g. Benkhelil, 1989). It is geographically sub-divided into three; Northern, Central and Southern Benue portionsMany researchers have contributed to the review of  the geology and stratigraphy of Benue Trough (e.g. Benkhelil, 1982, 1989; Zaborski, et al., 1997; Zarborski, 2000; Obaje et al., 2004; Sarki

Yandoka et al., 2015a, 2015b, 2016). The Northern Benue Trough experienced a compressional phase at the end of Maastrichtian which resulted in the folding and faulting of Pre-Palaeogene sediments. It is divided into two major sub-basins; the N-S trending Gongola sub-basin and the E-W trending Yola sub-basin (Sarki Yandoka et al., 2014; Guiraud and Maurin, 1992).

In the Gongola Sub-basin, Aptian - Albian sediments are represented by the alluvial fan to lacustrine to fluvial Bima Formation while the transitional Yolde Formation marked the Cenomanian sediments (Fig. 2). The Pindiga Formation represented by the marine Kanawa Member, the regressive fluvial and littoral sandy facies of the Gulani, the Dumbulwa and the Deba Fulani Members were deposited on the Cenomanian Yolde Formation. The Gombe Formation overlies the Campano-Maastrictian Fika Shale (Fig. 2). Tertiary sediments were restricted to the western part of the Northern Benue Trough where the continental Kerri-Kerri Formation unconformably overlies the Gombe Formation (Abubakar, 2014).

The stratigraphic succession in the Yola Sub-basin of the Northern Benue Trough (Fig. 2) comprises the continental Lower Cretaceous Bima Formation, the Cenomanian transitional marine Yolde Formation and the marine late Cenomanian–Santonian Dukul, Jessu, Sekuliye Formations, Numanha Shales and Lamja Formations (Carter et al., 1963; Abubakar, 2006). The Lamja Formation was earlier described as “Carbonaceous Beds" by Carter et al. (1963) and conformably overlies the Numanha Shales. It consists of a crystalline and shelly limestone, siltstone and yellowish to whitish fine-grained well bedded sandstone, dark grey shale and dark coals (Fig. 2) deposited in a relatively shallow marine environment. This formation terminates the sedimentation of the Yola Sub–basin (Carter et al. 1963; Guiraud, 1990).

Maiganga area (coalfield) is located in Gombe Formation within the Gongola Sub-basin of the Northern Benue Trough (Fig. 1). Previous studies indicates the presence of Late Senonian to Maastrichtian estuarine and deltaic shale, sandstones, siltstones and coal beds in Gombe Formation (Abubakar, 2006). Stratigraphic, tectonic and geochemical evidences in the Northern Benue Trough indicate similar evolutionary history with the adjoining basins in Chad, Niger and Sudan within the same rift trend termed West and Central African Rift System (Abubakar, 2014).

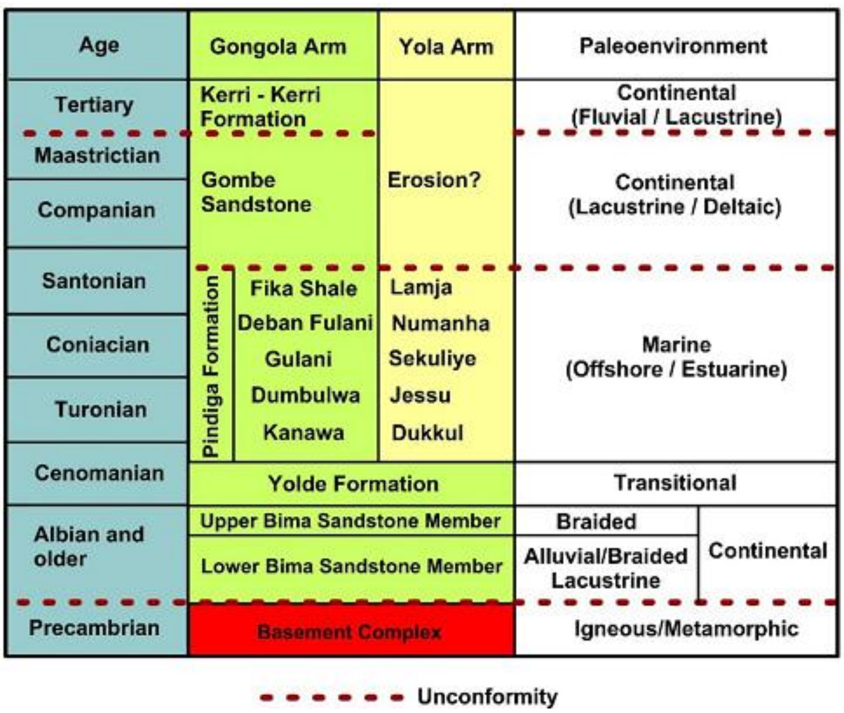


**Figure 2:** Stratigraphic succession of the Northern Benue Trough showing Gongola and Yola Sub-basins (modifed after Abubakar, 2006)

**Materials and methods**

Fieldwork was conducted during this study. Coal samples were collected from Maiganga and Lamza areas. A systematic sampling was carried out based on variation in lateral and vertical succession of the sedimentary facies. The samples were taken at about 1m interval vertically after removing weathered surfaces. All the samples were crushed to fine powder and screened with Source Rock Analyzer (equivalent to Rock Eval equipment). The samples were heated in the absence of oxygen to determine the source rock hydrocarbon potential (S1 and S2) and thermal maturity (Tmax) of rock facies. All samples were treated with HCl to remove CaCO3 and subsequently 100 mg of each sample were subjected to TOC Analysis using a multi N/C 3100 analyzer. Other parameters such as production index (PI), Hydrogen Index (HI) and production yield (Py) were calculated from the Rock Eval pyrolysis parameters and TOC. Polished blocks of about 0.3 cm grains were mounted in densification mixture of hardener and subsequently polished. Petrographic Analysis was performed under LEICA CTR 6000 Orthoplan microscope with ×50 oil immersion objectives using immersion oil with a refractive index (ne) of 1.518 at 23°C. Calibration for the reflectance measurement was done using a sapphire glass standard of 0.589% reflectance value while DISKUS software was used for capturing. Reflected white light was for vitrinite reflectance analysis measurement while ultra-violet light was also used maceral identification and capturing of flourescencing macerals. Reflectance measurements was carried out in the random mode (Rrand).

**Results and Discussion**

In this study, kerogen pyrolysis analysis (Rock-Eval Pyrolysis) and organic petrological studies (vitrinite reflectance and macerals identification) are presented. The results revealed information about organic matter type, thermal maturity/coal rank and possibility of hydroarbon genetrative potential.

***Pyrolysis anaysis***

Kerogen pyrolysis are used to provide information on the organic matter type (quality) of potential source rocks. Type I and II kerogen is commonly derived from lacustrine and marine source rocks and they are capable of generating liquid components of hydrocarbons. Although, Type III kerogens composed of mainly woody materials and are more susceptible to generate gas-prone whilst Type IV kerogens composed inert materials with no potential of generating hydrocarbons (Peters and Cassa, 1994). Total organic carbon content (TOC: wt %) gives a measure of the source rock richness for hydrocarbon generation (Peters and Cassa, 1994).

The coals samples of Maiganga and Lamza were analysed for the determination of TOC, S1, S2, Tmax, HI, and PI (Table 1). TOC analysis for the samples ranges from 0.9 to 80.0 wt% for maiganga coals and hydrocarbon yield (S2) from pyrolysis varies from 0.05 to 158.84 mgHC/g and HI values from 40.50 to 233.88 mgHC/gTOC. The S2 trend is high from 26.42 to 158.84 mgHC/g rock while Tmax is generally less than 435ºC in Maiganga area. For the Lamza coals, the hydrocarbon (S2) yields are ranging from 0.82 to 125.53 mg HC/g rock (Table 1). The pyrolysis S2 yields for the coals range from 45.49 to 125.53 mg HC/g rock.

The pyrolysis data (HI against Tmax) of Maiganga coals (Fig. 3) indicated that the analysed samples generally plot in the early to relatively mature zone of mixed Type III-II and predominantly Type III kerogens as indicated by the HI values in the range of 40.50 to 233.88 mgHC/gTOC (Table 1), suggesting that the sediments may be expected to generate mainly gas and limited components of liquid hydrocarbons. More so, samples that contain a Type III vitrinitic kerogen would be expected to generate gas with hydrogen index <200 mg HC/g TOC whilst samples with HI values higher than 200 mg HC/g TOC can generate oil and perhaps, their main generation products are gas and condensate (Hunt, 1996; Adedosu, 2009).

**Table 1: Pyrolysis analysis data of kerogen for Maiganga and Lamza coals**

| Sample ID | Lithology | TOC and Pyrolysis data (SRA) | | | | | |
|---|---|---|---|---|---|---|---|
| | | $S_1$ (mg/g) | $S_2$ (mg/g) | $T_{max}$ (°C) | HI | PI | TOC wt. % |
| **LZ2** | Coal | 2.51 | 100.67 | 437 | 209 | 0.02 | 48.28 |
| **LZ4** | Coal | 2.64 | 102.59 | 438 | 151 | 0.03 | 67.85 |
| **LZ6** | Coal | 1.88 | 92.42 | 439 | 188 | 0.02 | 49.15 |
| **LZ8** | Coal | 2.34 | 96.98 | 438 | 167 | 0.02 | 58.32 |
| **LZ10** | Coal | 2.89 | 125.53 | 436 | 194 | 0.02 | 64.67 |
| **LSS12** | Coal | 0.66 | 59.85 | 445 | 111 | 0.01 | 53.88 |
| **LSS14** | Coal | 2.61 | 100.79 | 437 | 158 | 0.03 | 63.98 |
| **MG1** | Coal | 0.33 | 130.06 | 430 | 162.60 | 0.003 | 80.0 |
| **MG3** | Coal | 0.27 | 158.84 | 420 | 202.60 | 0.002 | 78.4 |
| **MG5** | Coal | 0.70 | 123.36 | 418 | 186.34 | 0.006 | 66.2 |
| **MG7** | Coal | 0.63 | 59.17 | 422 | 85.26 | 0.011 | 69.4 |

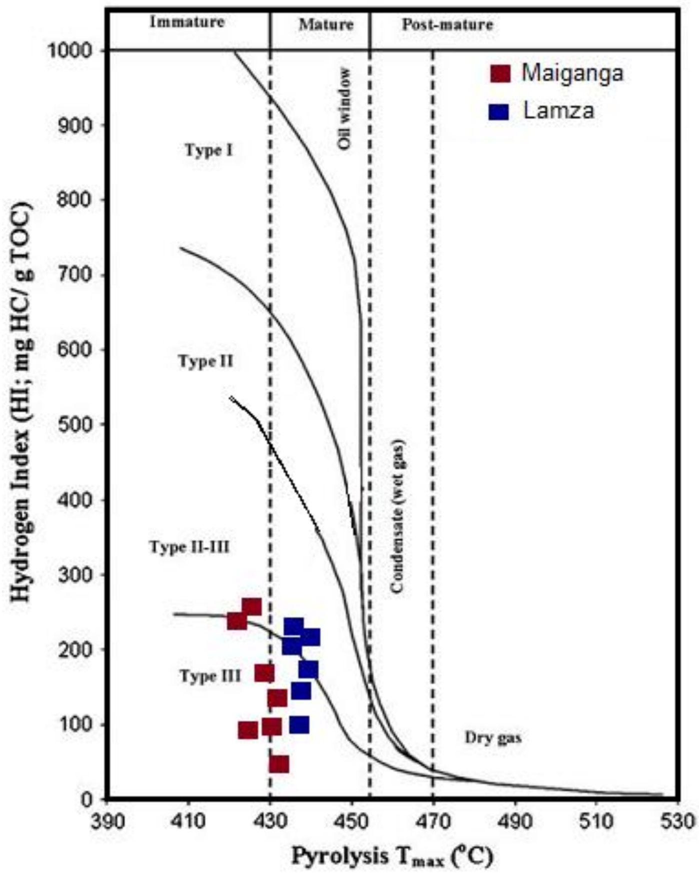


**Figure 3:** Hydrogen Index (HI) plotted against pyrolysis Tmax (°C) data showing Type III and Type II-III kerogen typing

The pyrolysis S2 yields for the Lamza coals range from 45.49 to 125.53 mg HC/g rock (Table 1). The hydrocarbon yields (S2) are in agreement with TOC content (Fig. 4), indicating that the Lamja coal sediments are fair to excellent source rock-generative potential based on classification given by Peters and Cassa (1994). The coal samples could become the most promising source rock for hydrocarbon generation as reflected by high pyrolysis yield (S2) and total organic carbon (TOC wt%) content (Sarki Yandoka, 2015).

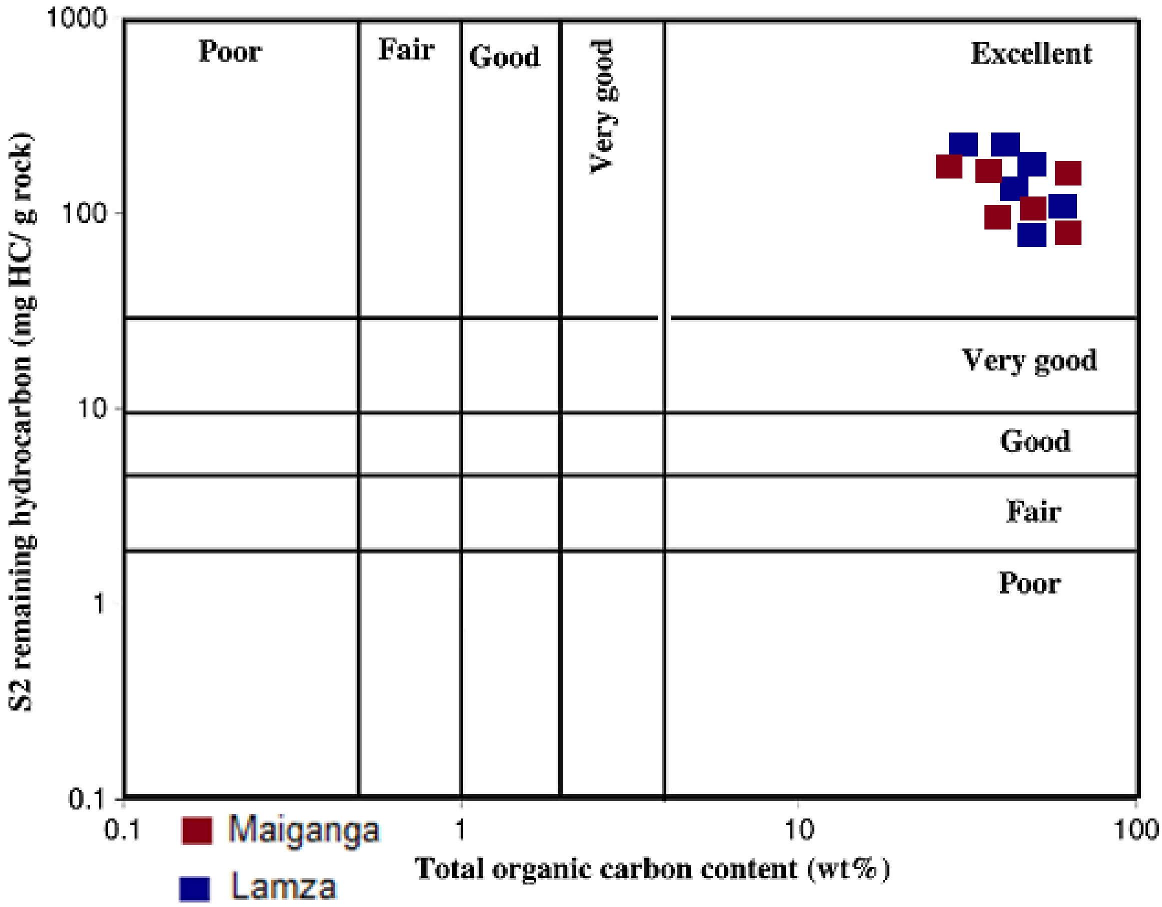


**Figure 4:** Remaining hydrocarbon (S2 yield) plotted against total organic carbon (TOC content) showing excellent source rock potential

***Petrological analysis***

Liptinite, vitrinite/humite and inertinite are the three basic maceral groups in coal and sedimentary rocks that display distinguishing characteristics under microscope in terms of colour, relief of polished surface, morphology (shape and structure) reflectance and fluorescence (Jauro et al., 2007; Hakimi and Abdullah, 2014). In this study, reflectance measurement of ulminite (low ranks equivalence of vitrinite and vitrinite reflectance measurement were conducted (Fig. 5). Mean reflectance measurement for Maiganga coals ranges from 0.26 to 0.36% whereby it is relatively low compared to that of the Lamza coals.

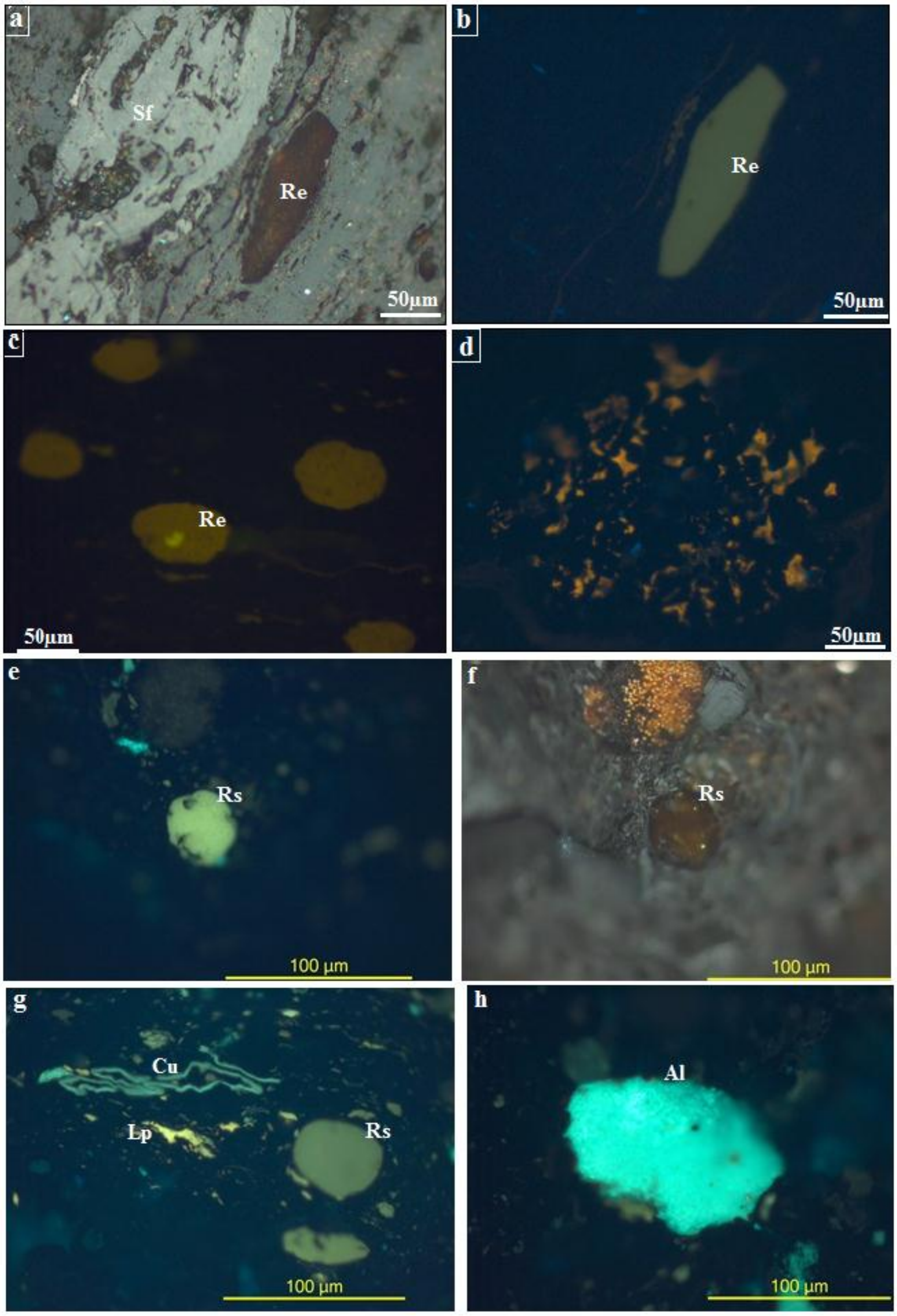


**Figure 5:** Photomicrographs of (a-d) Lamza coals showing resinite (re) and semifusinite (sf) and (e-h) Maiganga coals showing cutinite (cu), liptodetrinite (lp), resinite (rs) and Alginite (Al) under reflectance and UV lights excitation

In Maiganga coals, organic petrographic observations shows abundance of huminite/vitrinite compared to the liptinite and inertinite macerals. Most of the samples are dominated by attrinite/densinite, corpogellinite and textinite (Fig. 5) maceral of plant tissue as well as fusinite, semifusinite, inertodetrinite, scleroctinite under the reflected white light. Liptinite maceral such as sporinite, cutinite, resinite, liptodetrinite with few alginite were observed displaying varying shapes and colour (light green through bright yellow to brownish yellow).

The mean reflectance of vitrinite particles of Lamza coal sediments ranges from 0.57 to 0.82 %. The coal samples are rich in terrigenous liptinites especially resinite, sporinite and cutinite (Fig. 5). Macerals of the vitrinite group are identified as dark grey or medium grey tellinite, lighter colored vitrodetrinite and relatively darker desmocollinite. None of the vitrinites show any fluorescence. The macerals of the vitrinite group are significantly higher in abundance compared to the other maceral groups. The inertinite macerals have the lowest abundance in the coal samples and they are present as micrinite, fusinite, semifusinite, funginite and inertodetrinite (Fig. 5). The presence of liptinitic macerals in both Maiganga and Lamza coal samples is most apparent to the oil and gas prone nature of the analysed samples of mainly Type III-II and Type III kerogens (Peters and Cassa, 1994; Hakimi et al., 2013).

***Coal rank and hydrocarbon potential***

The degree of thermal maturity/coal rank of the organic facies determined by Tmax, is generally less than 435°C with Tmax, of 436°C in Maiganga. Hydrogen Index (HI, mgHC/gTOC) is a measure of oil generation potential of organic rich rocks based on the relationship between TOC and S2. In this case the HI is relatively high for Maiganga coal, indicating immaturity-early oil window. Integration of organic petrography results, Tmax (°C), can be used to infer, reliably, the source rock maturity (Peters and Cassa, 1994; Tissot and Welte, 1984). The vitrinite/huminite reflectance (%Ro) obtained using oil immersion objective is relatively low for Maiganga (an average value of 0.35 %Ro). The mean reflectance of vitrinite particles of the Lamza coals ranges from 0.57 to 0.82 % which corresponds to early mature to peak oil window maturity. This is supported by the plot of Tmax against PI (Fig. 6) indicating main hydrocarbon generation potential.

Several studies have been indicated that there is a direct correlation between pyrolysis data (HI) and hydrocarbon generation potential (e.g. Hunt, 1995). Quantity, quality, vertical and lateral extents of organic matter (OM) as well as thermal maturity are the crucial factors in determining a petroleum source rock potential. Total organic carbon content determination (TOC: wt. %) gives a measure of the source rock richness for hydrocarbon generation (Peters and Cassa, 1994). Liptinite, vitrinite/humite and inertinite are pathfinders for determining the hydrocarbon potential of sedimentary rocks.

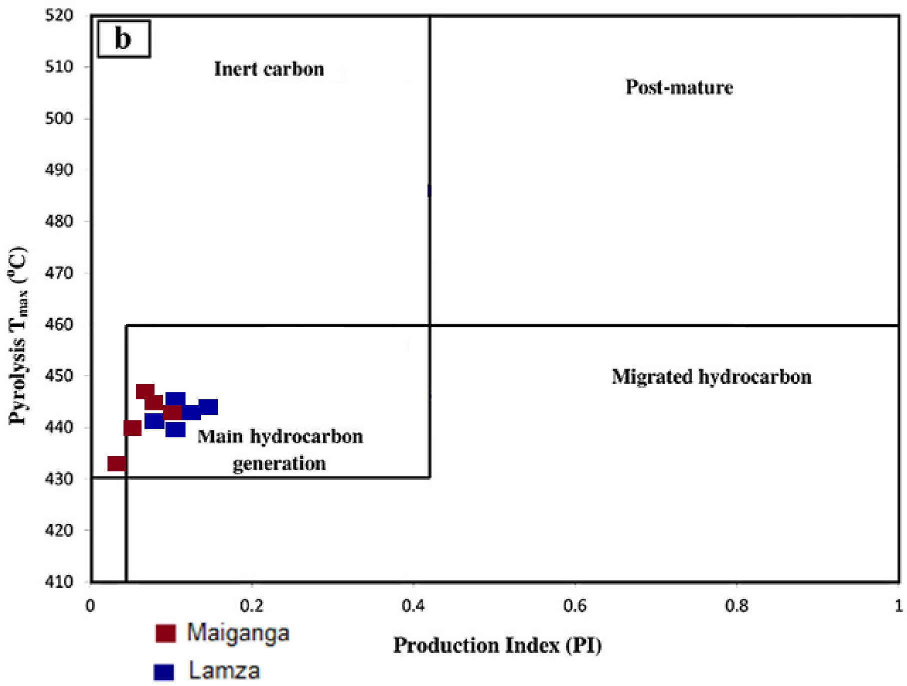


**Figure 6:** Pyrolysis Tmax (°C) plotted against Production Index (PI) indicating hydrocarbon generation level of the samples

In this study, the hydrocarbon potential of the source rocks in Maiganga and Lamza are assessed on the basis of pyrolysis and petrographic analysis. TOC values are categorized as excellent (>4), very good (2-4), good (1-2), fair (0.5-1) and poor (< 0.5) OM quantity for hydrocarbon generation (Peters and

Cassa, 1994). As would be expected for coals, the TOC results is excellent for Maiganga and Lamza coals. The analysed Maiganga coal can be classified as as capable of generating gas/oil (> 200 mgHC/gTOC).

Most of Lamza coals under current investigation have HI lower than 200 mg HC/g TOC can generate gas. The high gas-generation potential of the samples could be due to the high contribution of land plants input that were deposited under oxic conditions. Therefore, a high prospect for gas-prone hydrocarbon is anticipated from the from maiganga and Lamza coals of the Northern Benue Trough of Nigeria.

**Conclusion**

Kerogen pyrolysis (Rock-Eval pyrolysis and TOC content determination) and organic petrographic (vitrinite reflectance and macerals) characterisation of Maiganga and Lamza coals from Northern Benue Trough in other to determine the kerogen types, thermal maturity and hydrocarbon generation potential have shown that the sediments contain dominant terrestrial organic source origin of mainly Type III-II and Type III kerogens. The samples from Maiganga area are relatively immature to mature with major gas source rock potential (pre–oil generation window) while samples from Lamza area are at early-mature to peak oil window maturity with predominantly gas generative potential. The coals samples of Maiganga and Lamza areas have fairly mixed Type II-III and Type III kerogens and could be expected to generate major gas and limited components of liquid hydrocarbons. This study therefore, suggest that the Maiganga and Lamza coals could serve as ggod source rocks for the Upper Crectaceous petroleum system of the Northern Benue Trough as they possessed major gas and minor oil generating potential. This data however, could be used as a guide for the current frontier (oil and gas) exploration campaigns in the Northern Benue Trough of Nigeria.

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