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ASSESSMENT OF THE THERMAL MATURATION OF POSSIBLE HYDROCARBON SOURCE ROCKS FROM THE LOWER CRETACEOUS BIMA FORMATION, NORTHERN BENUE TROUGH, NORTH EAST NIGERIA

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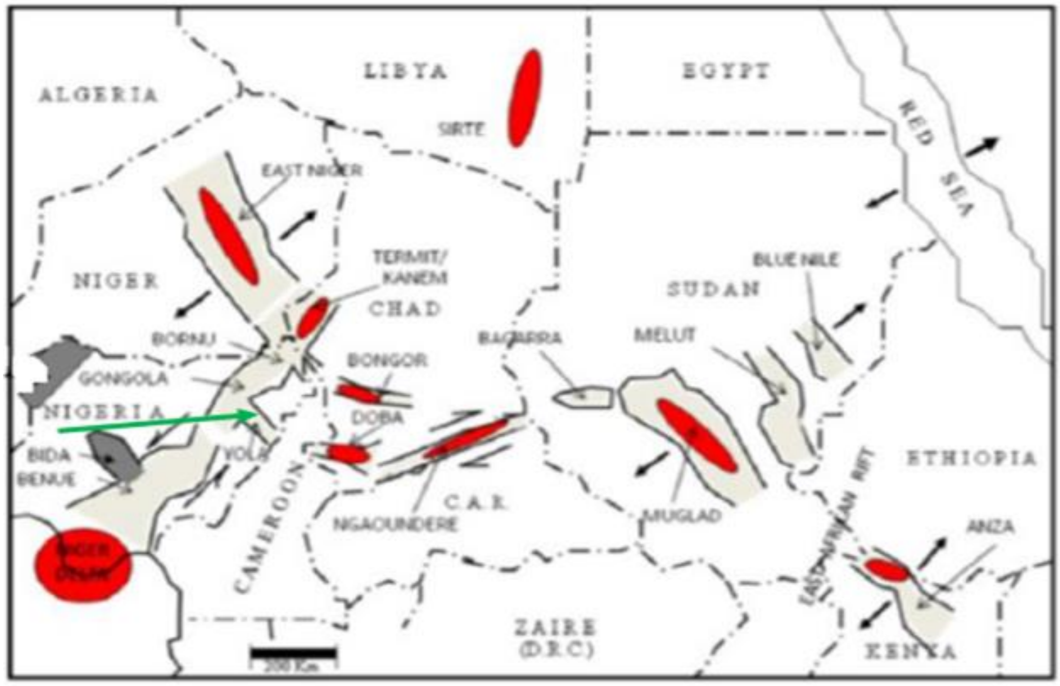
ABSTRACT
The oldest sedimentary unit in the Northern Benue Trough is the Early Cretaceous Bima Formation. This research is aimed at studying the sedimentary successions in Bima Formation in the Yola Basin with a view to understanding its hydrocarbon source rock maturity using palynological analysis with the aim to provide an overview of the type, quality and maturity of organic matter using spore coloration index and to examine the processes controlling organic matter enrichment in the sediments from subsurface data. One hundred and fifty (150) samples of shales, sandstone, siltstone and mudstone were subjected to palynological analysis using standard palynological preparation techniques. Visual color analysis was later carried out on the recovered palynomorphs. Microscopic analysis of the differences in spore and pollen color was performed on sporomorphs found in the samples. From the samples studied, the C.A.I (Colour Alteration Index) and T.A.I (Thermal Alteration Index) which ranges from 1.5-3.5 in conjunction with corresponding vitrinite reflectance of %R0 =2-3.5 suggesting the catagenetic stage and temperatures more than 120 °C, reveal that the source rocks of the Bima Formation in the Yola Basin are immature to very mature occurring within the oil and dry gas limit of hydrocarbon production. Though poor in sporomorph content, show indications of organic matter that is good to excellent quality with Kerogen type II and III as the main organic matter type present. When exposed to burial temperatures ranging from 60°C to 160°C, Type II and III kerogen produce the majority of the world's oil and gas.

Keywords: Thermal maturation, Spore Color, Kerogen, Lithofacies, Bima Formation

INTRODUCTION
Palynomorphs, such as sporomorphs and acritarch, are composed of impervious organic polymers, the precise nature of which is still unknown. One noteworthy feature of these polymers is the internal reorganization of their molecular structure, which is brought about by processes that occur during burial such as, depth and duration, geothermal flux, and fluid geochemistry (Aliyu et al 2024).
The Benue Trough is divided arbitrarily into three parts: the Central Benue Trough, which has depo-centers around Makurdi, Lafia, and Wukari; the Southern Benue Trough, which has depo-centers around Nkalagu and Abakaliki; and the Northern Benue Trough, which is further subdivided into the Gongola Basin and Yola Basin, with depo-centers around Pindiga, Ashaka, Tula, and Bambam, respectively.
Named by Falconer (1911) and detailed by Carter et al. (1963), the Early Cretaceous Bima Formation is the oldest unit of the sedimentary succession in the Northern Benue Trough. Their work served as the foundation for further reviews, such as those by Guiraud (1990), Zaborski et al. (1997), and Zaborski (1998, 2003). Studies have been carried out by authors such as Akande et al (1998), Obaje (2004), Abubakar et al (2008), Tukur (2015) and Shetima et al (2020) on the Bima Formation in the Gongola Basin.
This research is aimed at studying the sedimentary units in Bima Formation around Tula Village which is part of Yola Basin in order to understand the maturity of its source rock using palynofacies analysis in order to provide an overview of the quality, maturity and type of organic matter from subsurface data. There is also a knowledge gap regarding the thick dark shales, limestone, and sandstones of the Yola arm because the majority of published research on petroleum exploration in the Northern Benue Trough is focused on the Gongola arm (Adegoke et al., 1978; Zarboski et al., 1997; Obaje et al., 1998; Abubakar and Obaje, 2001; Ojo and Akande 2000; Nwojiji et al., 2013). The data from this study adds to our understanding of the Bima Formation in the Yola Basin and provides information on a number of characteristics, including the source rock's hydrocarbon potential and the kerogen source (terrestrial vs. marine).
While exploration for hydrocarbon and exploitation of carbonates for cement manufacturing is taking place within Gongola Basin, such activities are non – existent within Yola Basin, and this perhaps may have been responsible for the lean published works on its geology.
The contiguous rift basin which is similar to the study area which is Yola Basin (Douba Basin in Chad Republic) is known to have oil reserve of about 1 billion barrels (Obaje et al., 1998). The dark lithologies the basin was affected by the Tertiary extrusive volcanism – the Lunguda basalts which could have increased its geothermal heat content. Increased geothermal heat is expected to hasten up the process of generating hydrocarbon due to cracking of kerogen rich sediments of the basin such as shales, coals and carbonates.
Knowing the source rock maturity of sediments is very important because it helps in delineating the type of hydrocarbon in the area (whether it is oil prone or gas prone) and also whether it is matured enough to produce hydrocarbon.



Major oil and gas discovery Study Area

Figure 1: Regional tectonic maps of central and western African rifted basins showing the relationship of the Muglad, Doba and east Niger basins to the Nigeria's Benue Trough/Yola Basin. (Adapted from Schull, 1988; Obaje et al., 2004 made modifications).

Location and Accessibility of the Study Area

The area which is part of Yola Basin is Situated in the North Eastern part of Nigeria. It lies between longitudes 110 50'E and 110 55'E, and latitudes 90 45'N and 90 50'N. The basin is bordered in the north by Bornu Basin while its Northwestern boundary is Gongola Basin. Both Tula 1 and Tula 2 boreholes were drilled close to Tula village which is accessible through Gombe – Yola Road.

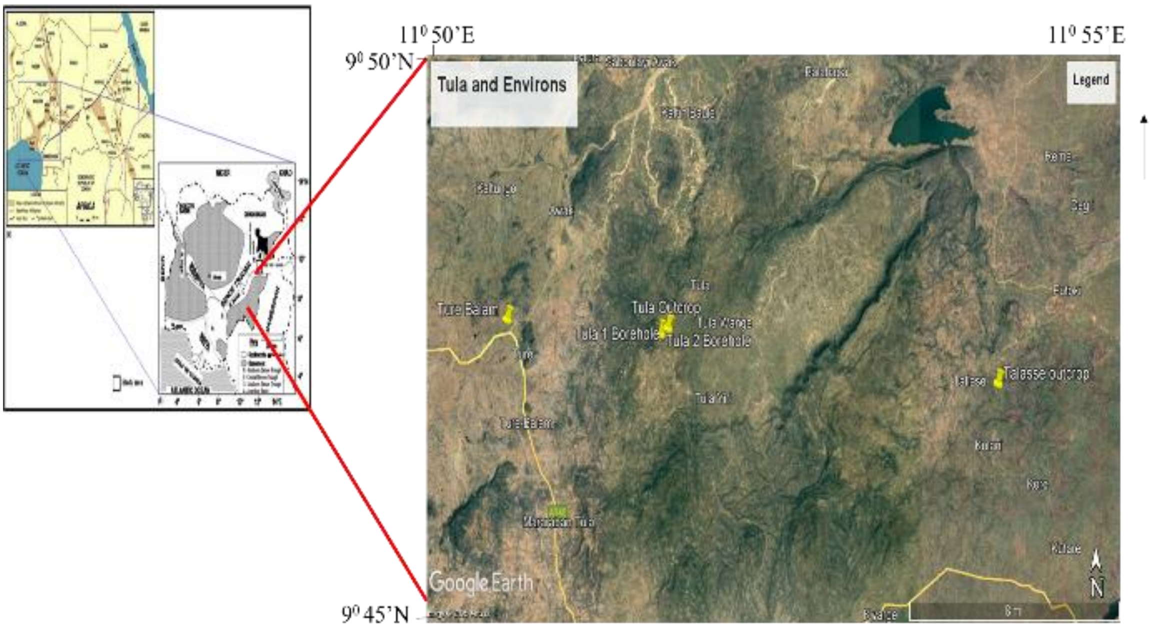


Figure 2: Google Map of the Study Area (inset: map of Nigeria, showing the location of Yola Basin)

MATERIALS AND METHODS

50 cuttings samples were obtained from Tula 1 and 100 cuttings from Tula 2 boreholes which were drilled at Lat. 9° 47' 56.9'' N and Long. 11° 26' 20.4'' E, and penetrated the Lower Cretaceous sedimentary succession in the Northern Benue Trough at Tula village area which is part of Bima Formation in the Yola Basin. The samples obtained were subjected to the palynological preparation technique of (Batten and Stead, 2005) to recover the palynomorphs from the sediments. 20grams of each of the Sample obtained were treated with HCl (35 %) under a fume cupboard and allowed to rest for 24hrs to remove the carbonates. HF (48 %) was

added after 24hrs to remove the silicates. Thereafter, the resulting residue was diluted with some distilled water and carefully decanted, then complete washing of the decanted samples with some distilled water in order to remove fluoro-silicate compounds which are usually formed from the reaction with HF. Two slides were produced per sample using glycerin jelly. Each sample was subjected to palynological analysis under an Olympus CX41 Binocular Light Transmitted Microscope.
The identification of palynomorphs and palynomacerals was accomplished with the help of palynological albums and the published works of earlier researchers, each palynomorph (pollen, spores and dinoflagellate), phytoclast and amorphous organic matter was counted separately. The total count of all particulate organic matter per sample was multiplied by the individual count for each particulate organic matter and divided by 100 to get the percentage count. The recovered palynomorphs were later subjected to Visual color analysis as suggested by Pearson, using visual comparison of the colors of the palynomorphs obtained with the Munsell color Standard.

RESULTS AND DISCUSSION

Tula 1 Borehole

Fifty samples were obtained and analyzed for this section. Phytoclasts constitutes the largest percentage of the analyzed sediments with moderate – low percentage of AOM and palynomorphs. The data in table 1 shows relative percentage of organic matter obtained in the analyzed sediments.
This shows the general environment of deposition of the analyzed sediments. The high percentage of phytoclasts and amorphous organic matter is an indication that the sediments are more terrestrial than aquatic which signifies that the area is likely to have more gas than oil (table 5).

Table 1: Relative Percentage of Organic Matter Obtained from Tula 1 Borehole

Depth	Phytoclasts	AOM	Palynomorphs	Total
1 - 5	52.51	43.31	2.22	100
5 - 10	51.71	45.21	3.1	100
10 - 15	62.9	34.81	2.31	100
15 - 20	72.12	27.4	0.5	100
20 - 25	65	35.02	0.02	100
25 – 30	52.01	46.74	1.15	100
30 - 35	49.11	47.78	3.2	100
35 - 40	67.33	32.49	0.22	100
40 - 45	71	29.79	1.23	100
45 - 50	69.11	31	0.11	100

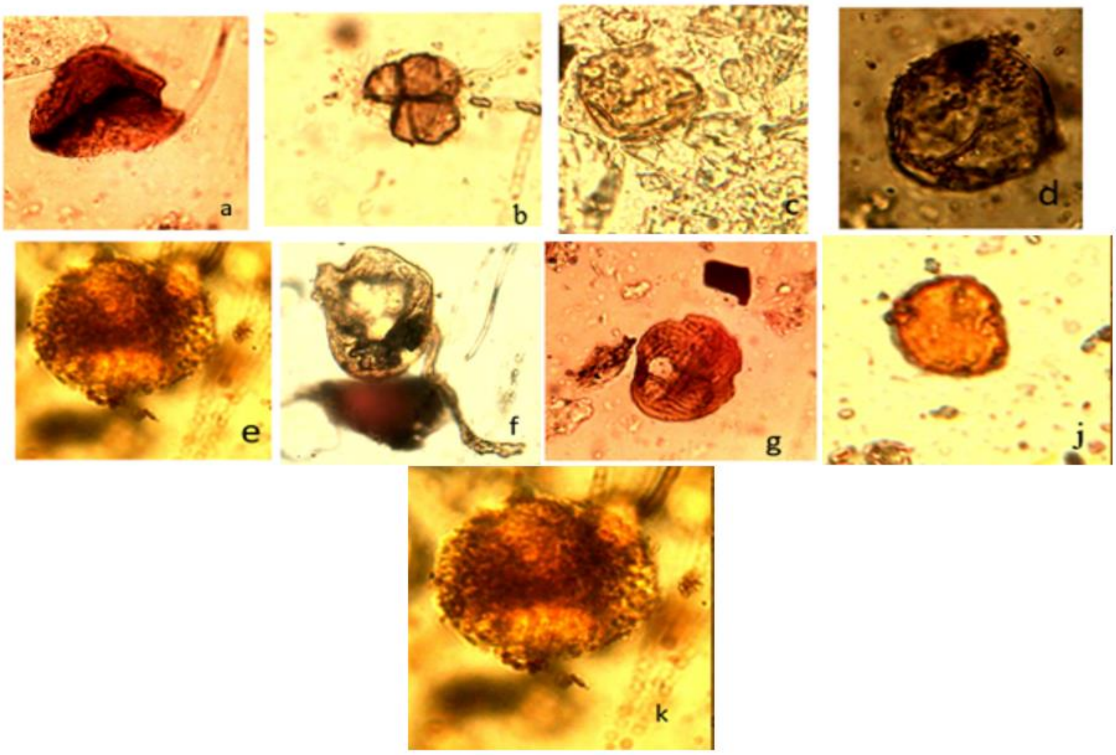


Plate 1: Showing some recovered palynomorphs from Tula 1 borehole section
a. Murospora sp., b. Classopollis Clasoides, c. Matonisporites equexinus, d. Araucariacites australis, e. Afropollis jardinus, f. Elaterosporites verrucatus, g. Cicatricosisporites spp., i. Stellatopollis spp., j. Microfoveolatosporites skottsbergii, k. Afropollis zonatus

Tula 2 Borehole

100 samples were obtained and analyzed in this section. Phytoclasts constitutes the largest percentage of the analyzed sediments with moderate – low percentage of AOM. The high percentage of phytoclasts indicates that the environment of deposition is more terrestrial than aquatic which signifies that the area is likely to have both oil and gas with a larger quantity of gas (table 5). The data in table 2 shows relative percentage of organic matter obtained from the analyzed sediments.

Table 2: Relative Percentage of Particulate Organic Matter Obtained from Tula 1 Borehole

Depth	PHYT	AOM	PAL	Total
0 - 5	0	0	0	0
5 - 10	62.91	37.45	1.52	100
10 -15	61.23	34.52	0.41	100
15 - 20	52.55	45.45	2.01	100
20 - 25	59.22	40.52	0.45	100
25 - 30	62.41	46.45	1.55	100
30 - 35	59.51	40.11	0.61	100
35 - 40	60.11	38.22	2.1	100
40 - 45	61.72	36.21	1.44	100
45 - 50	61.99	38.45	0.11	100
50 - 55	58.99	40.03	1.47	100
55 - 60	61.95	48.45	0.05	100
60 - 65	59.85	39.25	1.11	100
65 - 70	60.91	37.81	1.4	100
70 - 75	61.75	38.47	0.14	100
75 - 80	59.81	40.21	1.43	100
80 - 85	62.51	36.51	1.44	100
85 - 90	60.55	39.57	0.05	100
90 - 95	51.97	47.45	0.44	100
95 - 100	52.11	46.45	1.25	100

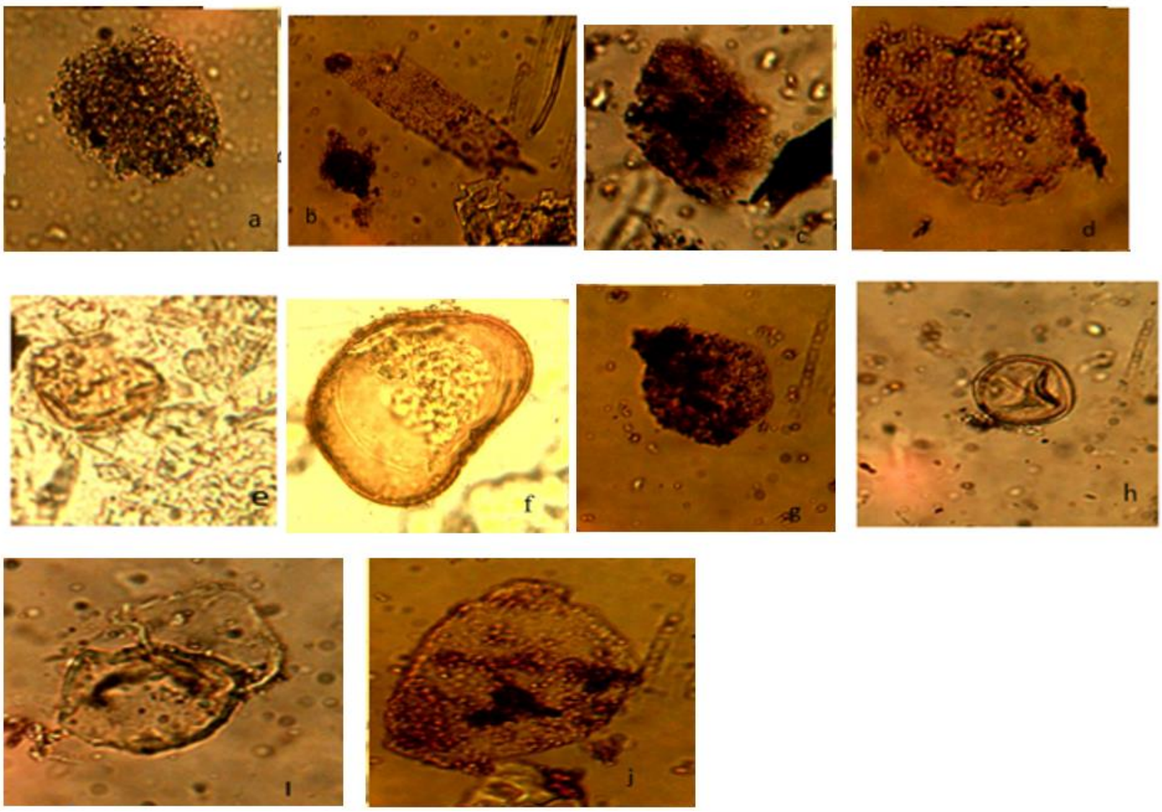


Plate 2: showing some palynomorphs recovered from Tula 2 borehole section
a. Afropollis operculatus, b. Ephedripites aegyptiaca, c. Stellatopollis barghoorni, d. Retimonocolpites variplicatus, e. Matonisporites equexinus, f. Microfoveolatosporites skottsberghii g. Retiacolpites colomellatus h. Biretisporites potoniaei, I. Dicheiropollis etruscus, j. Retimonocolpites ghazalii

Thermal Maturation

Table 3:Shows parameters used for measuring thermal maturation

Colour of Palyno-fossils	TAI	VRo%	Tmax	Paleo Temp oC	Hydrocarbon generation		
					Oil window	Wet gas window	Dry gas
Pale yellow	1.0	0.20			DRY GAS (EARLY CATAGENETIC STAGE) CONDENSATE FROM RESINITE		
Yellow	1.3	0.24					
Sunny yellow	1.7	0.28					
Yellow orange	2.0	0.30	420	75			
Bright orange	2.3	0.48	430	80	OIL WINDOW		
Orange	2.7	0.70	445	130			
Yellow brown	3.0	1.13	460	190		WET GAS WINDOW	
Dark yellow Brown	3.3	1.26	470	200			
Very dark grayish brown	3.7	2.00	500	235			DRY GAS THERMOGENETIC
Very dark gray	4.0	3.50	500	290			
Black opaque	5.0	5.55		290			

Table 4: Classification of Thermal Maturity

Maturation	RO (%)	Tmax (oc)	TAI
Immature	0.2-0.6	<435	1.5-2.6
Early mature	0.6-0.65	435-445	2.6-2.7
Peak	0.65-0.9	445-450	2.7-2.9
Late mature	0.9-1.35	450-470	2.9-3.3
Post mature	>1.35	>470	>3.3

Table 5: Types of Kerogens and their Hydrocarbon potential

Environments	Kerogen Type	Kerogen Form	Origin	HC Potential
Aquatic	I	Alginite	Algal bodies	
		Amorphous kerogen	Structureless debris of algal origin	
	II		Structureless planktonic material, primarily of marine origin	Oil
Terrestrial		Exinite	Skins of spores and pollen, cuticle of leaves and herbaceous plants	
	III	Vitrinite	Fibrous and woody plant fragments and structureless, colloidal humic matter	Gas and some oil Mainly gas

Thermal Maturation Analysis

The thermal maturity of the organic matter found in the studied samples was determined using spore color analysis based on Pearson's spore color chart which was correlated with other maturation parameters such as Thermal alteration index (TAI) and depth were considered together with the vitrinite reflectance (R_0 %), and maximum temperature (Tmax), gotten from the rock eval pyrolysis data conducted by Sarki Yandoka (2015). R_0 value of 0.45% signifies oil generation and values less than that defines diagenesis stage in which the source rock is determined to be immature, R_0 value of between 0.5-0.7% indicates the beginning of oil generation. R_0 of 0.9 1.3% indicates oil window, which is the major zone of oil generation. R_0 of 1.3-2% represent the late catagenesis stages in wet gas condensate and R_0 greater than 2% shows the metagenesis stages in which source rock is over mature and methane gas is the only hydrocarbon. Furthermore, TAI of 1.5 to 2.6 and Tmax of < 435℃ indicates source rocks that are immature, TAI of 2.6 to 2.7 and Tmax of 435-445℃ is an indication of early mature, TAI of 2.7 to 2.9 and Tmax of 445-450℃ indicates peak of maturity, TAI of 2.9 to 3.3 and Tmax of 450-470℃ shows late maturity and TAI of >3.3 with Tmax of >470℃ indicates postmature

Table 6: Microscopic Observation of Spore/pollen Colour Changes and their Corresponding Degree of Maturation and Thermal Alteration Index (TAI) in Tula 1 Borehole

Depth(m)	Lithology	Spore/pollen colour	TAI	Maturation
0 - 5	Light brown sandstone and siltstone	Pale Yellow	1.5	immature
5 - 10	Light - Dark brown sandstone	Pale Yellow	1.6	immature
10 - 15	Light - Dark brown sandstone	Pale Yellow	1.7	immature
15 - 20	Dark grey mudstone	Deep yellow	1.8	Early mature
20 - 25	Dark brown sandstone and siltstone	Deep yellow	1.9	Early mature
25 - 30	Dark brown siltstone	Deep yellow	2.1	Early mature
30 - 35	Dark grey mudstone	Light brown	2.3	Mature
35 - 40	Dark brown siltstone	Light brown	2.4	Mature
40 - 45	Dark brown sandstone	Light brown	2.4	Mature
45 -50	Dark grey mudstone	Light brown	2.5	Mature

In Tula 1 borehole, from 0 – 15m falls under spore color number 1 /2 which corresponds to spore color pale yellow to lemon yellow which shows that the organic matter is immature with a TAI of 1.5 to 1.8. From 15 – 30m falls under spore color number 2/3 and corresponds to deep yellow which shows that the organic matter is immature – early mature with a TAI of 1.9 – 2.1. From 30 – 50m falls under spore color number 5/6 which corresponds to light brown indicating that the organic matter is early mature - mature with a TAI of 2.1 – 2.5. This shows that Tula 1 borehole is immature to early mature and is still at the stage of mid-diagenesis of the process of hydrocarbon production. The type of organic matter, that is type II/III kerogen which indicates oil/gas prone.

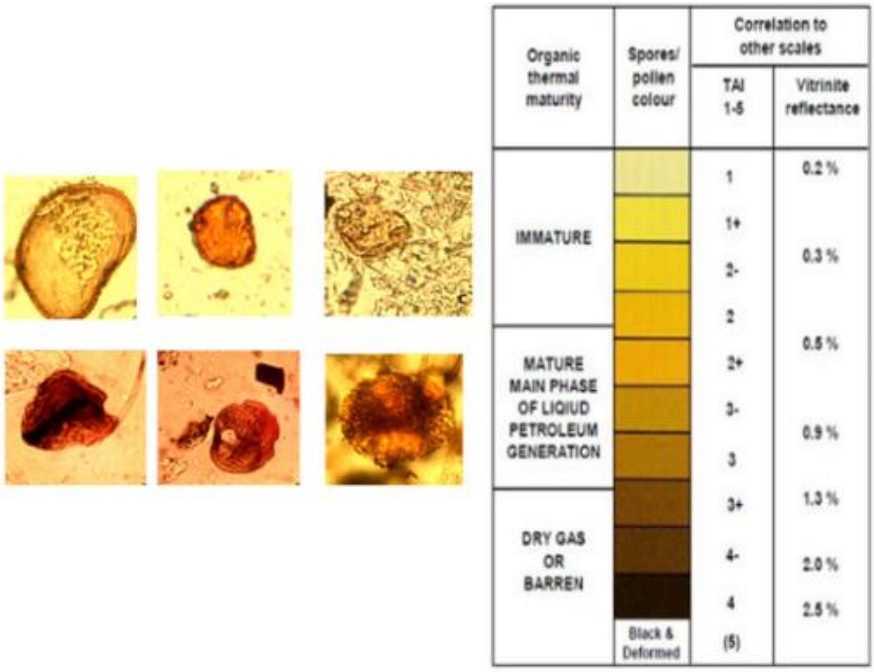


Figure 3: Correlation of Pollen/spore colour of the Sediments Investigated with Thermal Maturation Scales for Tula 1 Borehole (After Pearson, 1984)

Table 7: Microscopic Observation of the Changes in Spore/pollen and their Corresponding Thermal Alteration Index (TAI) and the Degree of Thermal Maturity in Tula 2 Borehole

Depth(m)	Lithology	Spore/pollen colour	TAI	Maturation
0 - 10	Light brown sandstone	Yellow	2.3	immature
10 - 20	Dark brown siltstone	Yellow	2.4	immature
20 - 30	Light grey shale and mudstone	Yellow	2.6	Early mature
30 - 40	Light grey shale and light brown sandstone	Light brown	2.7	Early mature
40 - 50	Light grey shale and mudstone	Light brown	2.7	Early mature
50 - 60	Light grey shale and mudstone	Light brown	2.7	Early mature
60 - 70	Light grey shale and mudstone	Dark brown	2.8	Mature
70 - 80	Light brown sandstone	Dark brown	3.1	Mature
80 - 90	Light grey mudstone	Dark brown	3.3	Mature
90 -100	Light grey shale	Dark brown - black	3.5	Mature – very mature

In Tula 2 borehole, from 0 – 30m falls under spore color number 2 which corresponds to spore color yellow which is an indication that, the organic matter is immature with a TAI of 2.3 to 2.4. From 30 – 60m falls under spore color number 4 which corresponds to light brown which is an indication that the organic matter is early mature with a TAI of 2.6 - 2.7. From 60 – 90m falls within spore color number 6/7 which corresponds to light brown which indicates that the organic matter is mature and has a TAI of 2.8 – 3.3. From 90 – 100m has spore color number 9 which corresponds to dark brown and is an indication that the organic matter is post mature with a TAI of 3.5. This shows that Tula 2 borehole is immature to post - mature and is still at the stage of mid-diagenesis to late diagenesis of production process for hydrocarbon. The organic matter type, is mainly type II/III kerogen which indicates oil/gas prone, meaning that the sample could have been able to generate oil and gas if subjected to the appropriate temperature for the generation of hydrocarbon.

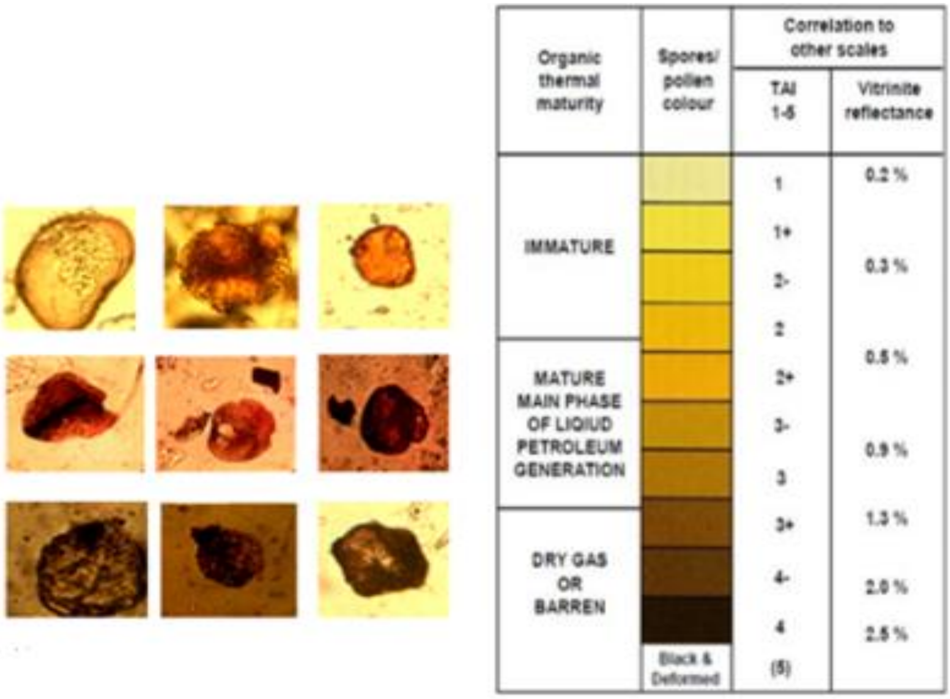


Figure 4: Correlation of Pollen/spore Colour of the Sediments Investigated with Thermal Maturation Scales for Tula 2 Borehole (After Pearson, 1984)

Discussion

The thermal maturation of the investigated sediments for both Tula 1 and Tula 2 boreholes ranges from 1.5 to 3.5 on the pollen/spore color index of Pearson (1984), according to the semi-quantitative evaluation of Early Cretaceous sediments of the Bima Formation in the Yola Basin, which was conducted by visually comparing sporomorph colors to Munsell color standards in conjunction with vitrinite reflectance. This indicates that they have reached their maximum maturation level to expel hydrocarbon.

Based on the samples analyzed, TAI starts from 1.5 -3.5. The lower section of Tula 2 borehole had a TAI of 3 which is approximately equivalent to vitrinite reflectance %R0 =2-3.5 indicating a catagenetic stage with temperatures of more than 120 °C.

This result is in tandem with Rock-Eval pyrolysis data for shales sediments obtained from Bima Formation available in the geological record (Sarki Yandoka et al., 2017), where he carried out a pyrolysis GC to investigate the source rock maturity of some lower Cretaceous sediments from the Bima Formation in the Yola Basin which indicates a Tmax (435-5080C), vitrinite reflectance (0.65-2.35 %R0) which show that shales of the Bima Formation are organically and thermally matured to act as a petroleum source rock in the Northern Benue Trough.

CONCLUSION

The thermal maturity of the source rocks of the Bima Formation in the Yola Basin ranges from immature to highly mature, occurring within the oil and dry gas window of hydrocarbon production, according to the C.A.I. and T.A.I. (which range from 1.5 to 3.5) and corresponding vitrinite reflectance. Despite having a low sporomorph concentration, they exhibit signs of good to exceptional quality organic matter, with Kerogen types II and III being the most prevalent types. When exposed to burial temperatures ranging from 60°C to 160°C, Type II and III kerogen produce the majority of the world's oil and gas.

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