Evaluation of Time-Temperature Index and Vitrinite Reflectance for Hydrocarbon Maturity in Parts of Niger Delta Sedimentary Basin, Nigeria

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Abstract: **- Lopatin method of the time-temperature index (TTI) and vitrinite reflectance were used for evaluating the hydrocarbon maturity level in parts of the eastern Niger Delta sedimentary basin. The TTI values were computed from the burial and thermal history of the basin while the vitrinite reflectance was computed from bottom hole temperature logs of oil wells in the area. The time-temperature index analysis was carried out for five horizons; A, B, C, D, and E in the basin. The results show that horizons A and B are immature (TTI < 15). Horizon C has just attained the maturity level (TTI ≈ 15) at a depth of 3200 metres. Horizons D and E are mature and are both oil (TTI > 150) and gas (TTI >165) producing. The values of the vitrinite reflectance show that oil generation starts from a depth of about 3000 metres. The results of both TTI and vitrinite reflectance show that hydrocarbon generation start from about 25 Ma upwards. The maturation level obtained from the TTI values agree with that obtained from the vitrinite reflectance**

Keywords: **Hydrocarbon maturity; Temperature; Vitrinite reflectance, Niger Delta**

I. INTRODUCTION

Modeling of geochemical processes involves the generation of petroleum and related maturation parameters, such as vitrinite reflectance, molecular biomarkers, and mineral diagenesis. The origin of petroleum can be described generally by three successive stages: diagenesis, catagenesis, and metagenesis[21]. Oil and gas are usually generated during the catagenesis stage when kerogen is thermally cracked to heavier and lighter hydrocarbons. The transformation rate is a function of the type of organic matter present and time-temperature history. The generation of petroleum hydrocarbon from thermal reactive organic matter during burial is a part of the overall process of thermal metamorphism of organic matter. This process is known as "organic metamorphism or thermal alteration" [12, 19]. Several models have been used for calculating the thermal maturity at different depths within a sedimentary basin. Two of these techniques are the [15]method of Time-Temperature Index (TTI) and vitrinite reflectance. The modified Lopatin method will be used in this work[23].

The [15]method of Time-Temperature Index (TTI) is used in this research to evaluate the petroleum generation potential of the study area. The TTI technique is based on the assumption that the chemical reactions that generate oil and gas are dependent on the temperature history of a hydrocarbon generating source rock and time of heating. Lopatin's method is a simplified version of the Arrhenius equation that states that chemical reaction rates increase exponentially with increasing temperatures. Lopatin simplified the Arrhenius equation by replacing the thermodynamic variables within the Arrhenius equation with a simple constant (r) that reflects the increase in reaction rate that results from increasing temperature. In general, chemical reaction rates tend to double with every 10^{o}C rise in temperature. The Time-Temperature Index is generated from a burial history of a sedimentary basin.The method has been used by some researchers in different sedimentary basins[16,11, 2, 10]

Vitrinite is a type of organic matter commonly found disseminated in sedimentary rocks and it represents the remains of woody plant materials that can be found in organic-rich rocks of terrestrial provenance. During burial diagenesis, loss of volatile components and graphitization of carbon results in an increase in the optical reflectivity of vitrinite.Vitrinite reflectance has become the most widely used measure of thermal maturity indicator in sedimentary rocks [6]. Recent kinetic models and field studies [3, 4]suggested that for heating periods greater than 10^4 years maximum temperature and not the duration of heating largely determines the level of reflectance.The time of hydrocarbon generation and expulsion in the Niger Delta basin has been reviewed by [11]. The time-temperature index and vitrinite reflectance of the study area have been used to evaluate the petroleum generation potential of thestudied area.

II. STUDY AREA

The study area(Figure 1) is located in the eastern parts of the onshore Niger Delta basin, Nigeria, The Niger Delta lies approximately within longitudes 5^0 and 7^0 east, and latitudes 4^0 and 6^0 north. The Niger Delta Basin is an extensional rift basin located in the Gulf of Guinea The basin carries high economic value as it contains productive petroleum system. The sediment fill has a thickness between 9 and 12 km.

The Niger Delta Basin was formed by a failed rift junction during the separation of the South American plate and the African plate, as well as the opening of the South Atlantic. Rifting in this basin started in the late Jurassic and ended in the mid-Cretaceous. As rifting continued, several faults (mainly thrust faults) were formed. Also at this time, we have the deposition of the syn-rift sands and then shales in the late cretaceous. The overall basin is divided into different zones such as the extensional zone, transition zone, and contraction zone due to its tectonic structure. There is an extensional zone, which lies on the continental shelf, which is caused by the thickened crust. There is a transition zone, and then there is a contraction zone, which lies in the deep sea part of the basin.

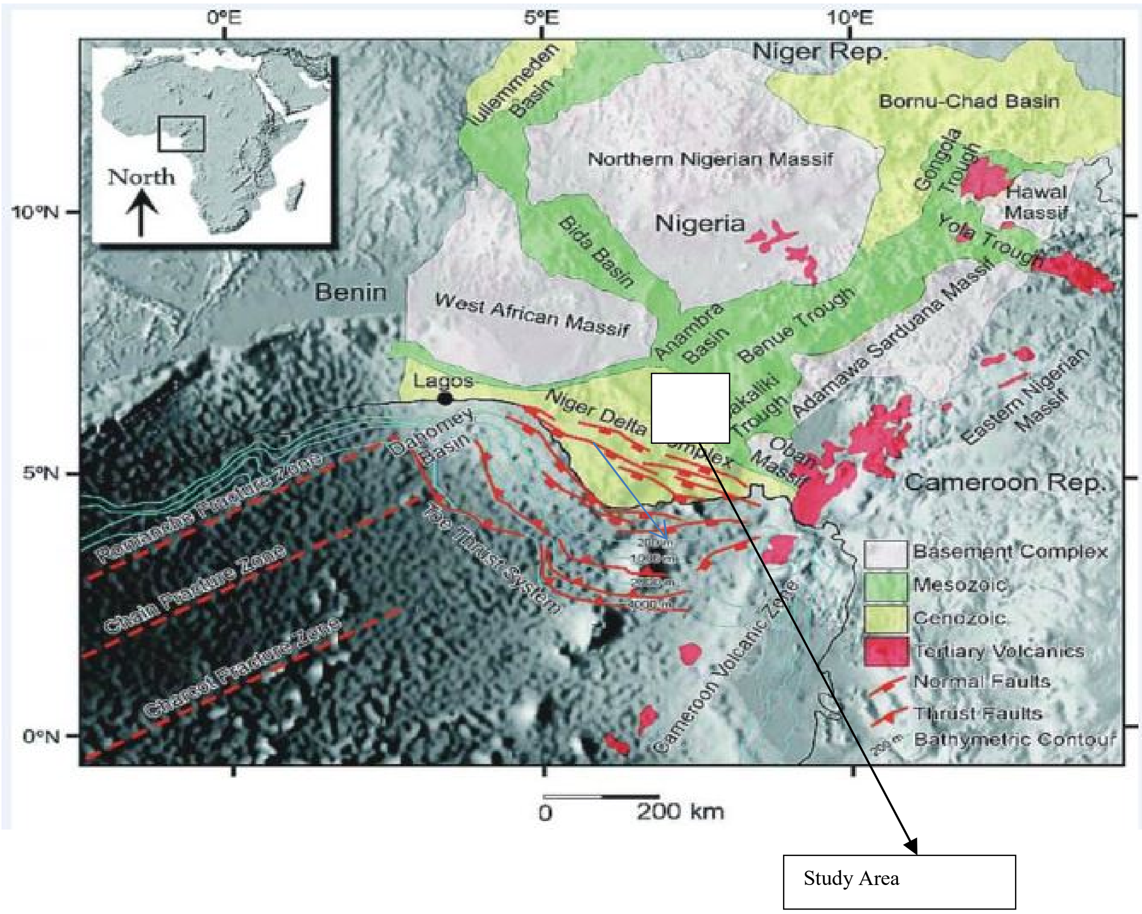

Figure 1: Niger Delta Region showing the main sedimentary basins and tectonic features[8].

The tectonic structures in the Niger Delta Basin are very typical of an extensional rift system, but the added shale diapirism due to compression makes this basin different. The main method of deformation is due to gravitational collapse of the basin, although the older faulting and deformation in the basin are related to the continental breakup and rifting of the African plate and South American plates. The overall basin is divided into a few different zones due to its tectonic structure. There is an extensional zone, which lies on the continental shelf that is caused by the thickened crust. There is a transition zone, and then there is a contraction zone, which lies in the deep sea part of the basin. Basin Inversion is caused by uplift and/or compression in this basin. The compression is caused by the toe detachment of the shale diapirs.

The Tertiary section of the Niger Delta is divided into three formations (Figure 2), representing prograding depositional facies that are distinguished mostly based on sand-shale ratios. The type sections of these formations are described and summarized in a variety of papers[1,9,13].

The Akata Formation at the base of the delta is of marine origin and is composed of thick shale sequences (potential source rock), turbidite sand (potential reservoirs in deep water), and minor amounts of clay and silt. Beginning in the Paleocene and through the Recent, the Akata Formation formed during lowstands when terrestrial organic matter and clays were transported to deep water areas characterized by low energy conditions and oxygen deficiency [18].It is estimated that the formation is up to 7,000 meters thick [9]. The formation underlies the entire delta and is typically overpressured. Turbidity currents likely deposited deep-sea fan sands within the upper Akata Formation during the development of the delta [7]. Deposition of the overlying Agbada Formation, the major petroleum-bearing unit, began in the Eocene and continues into the Recent. The formation consists of paralicsiliciclastics over 3700 meters thick and represents the actual deltaic portion of the sequence. The clastics accumulated in delta-front, delta-topset, and fluvial-deltaic environments. In the lower Agbada Formation, shale and sandstone beds were deposited in equal proportions, however, the upper portion is mostly sand with only minor shale interbeds. The Agbada Formation is overlain by the third formation, the Benin Formation, a continental latest Eocene to Recent deposit of alluvial and upper coastal plain sands that are up to 2000 m thick [1].

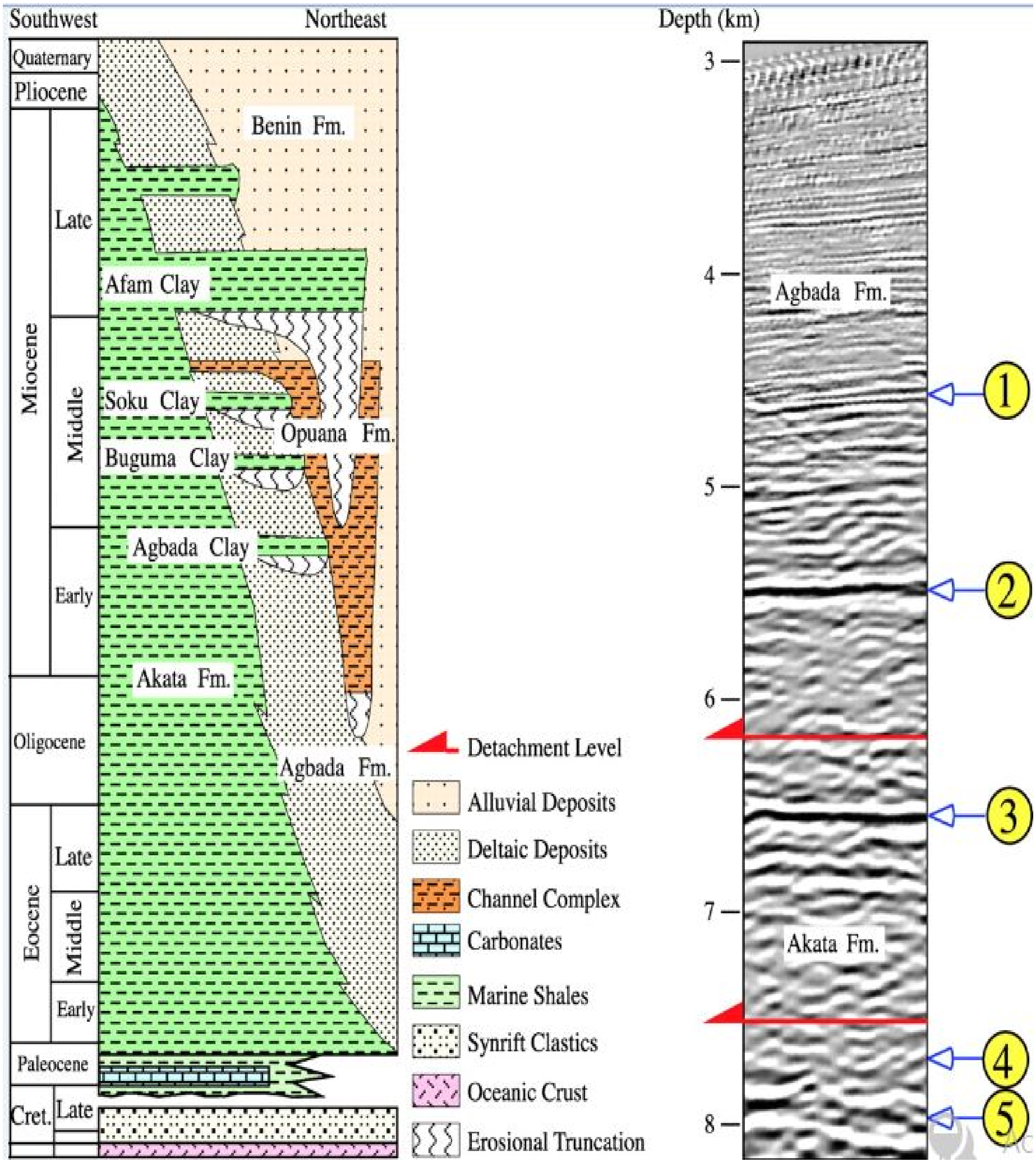

Figure 2: Schematic diagram of the regional stratigraphy of the Niger Delta and variable density seismic display of the main stratigraphic units. Modified from[14].

III: MATERIALS AND METHODS

The datasets used for this work are corrected bottom-hole temperatures, burial history, geothermal gradient and surface temperature of the eastern Niger Delta. The two methods used for assessing the hydrocarbon maturity level of the area are the modified Lopatin's model by[23] and Vitrinite reflectance. Lopatin's model is also known as the TTI method.

A: Calculation of Time-Temperature Index

The Lopatin's time-temperature index (TTI) of hydrocarbon maturity is based on the fact that hydrocarbon maturity and generation is a function of both temperature and duration of heating. According to[23], the maturity level attained by a rock unit over a duration of time t_1 and t_2 is given as

$$TTI = \sum_{n_{min}}^{n_{max}} (\Delta T_n)(r^n) \qquad 1$$

where

n_{max} and n_{min} = the n-values of the highest and lowest temperature intervals encountered by the rock unit

ΔT = length of time in millions of years spent by the sediment in the temperature interval

r = 2.

In developing the model, Lopatin divided the temperature profile into 10^0C intervals and drew the isotherms. He then chose 100 to 110^0C interval as the base interval and assigned to it an index value of n = 0. The other intervals were assigned index values as shown in Table 1

Table1: Temperature Factors For Different Temperature Intervals

Temp interval (^{0}C)	Index value (η)	Temperature factor (γ)
30 – 40	- 7	r^{-7}
40 – 50	- 6	r^{-6}
50 – 60	-5	r^{-5}
60 – 70	-4	r^{-4}
70 – 80	-3	r^{-3}
80 – 90	-2	r^{-2}
90 – 100	- 1	r^{-1}
100 – 100	0	1
110 – 120	1	r
120 – 130	2	r^2
130 – 140	3	r^3

The application of equation 1 is based on the believed that thermal maturity accumulates linearly with time and doubles with each 10^oC increase with temperature. To apply equation 1, we begin with a reconstruction of the depositional and tectonic history of the sedimentary basin by plotting depth of burial versus geological age and also by specifying its temperature history.

The temperature-history was specified for every depth throughout the geologic past. This was done by computing thepresent geothermal gradient (31^0C/Km)measured from continuous temperature log of oil wells in the study area. It wasassumed that both the gradient and surfacetemperature (i.e 27^0C, [22]) has remained the same through geologic history. The constructed burial-history curves and temperature grids werethen superimposed. Thepoints of intersection of the burial history curve with each isotherm were then marked out. These points ofintersection define the time and temperature intervals used in the estimation of the hydrocarbon maturity level.

B: Calculation of Vitrinite reflectance

Vitrinite reflectance is a measurement of the percentage (%) of light reflected from sample calibrated against a material that shows approximately 100% reflectance e.g. a mirror. Many workers have proposed equations relating temperature (T) and vitrinite reflectance (R_0)[6, 17, 5]. We prefer the Barker (1988) relationship between temperature and vitrinite reflectanceas it most closely matches the results predicted by kinetic models [20]. The model is given as

$$T\left({}^0C\right) = 104\left(InR_0\right) + 148 \qquad 2$$

Where

R_0 = Vitrinite reflectance

$T(^0C)$ =measured temperature

From equation 2, the vitrinite reflectance is given as

$$R_{predicted} = \frac{Exp(T\ {}^0C - 148)}{104} \qquad 3$$

Vitrinite reflectance is usually recorded as R_0 %. Vitrinite reflectance measurement plotted against depth. The R_0 profiles provide a great deal of information on the thermal history of the basin. The 'normal' pattern is a sublinear relationship between log R_0 and depth indicating a continuous-time-invariant geothermal gradient. R_0 profiles with distinct kinks between two linear segments (dog legs) indicate two periods of different geothermal gradient separated by thermal events. R_0 profiles with a sharp break or jump (offsets) indicate the existence of an unconformity with a larger stratigraphic gap. R_0 profiles in the sedimentary basin can, therefore, be used to test between the time constant and time-variant geotherms if the subsidence history is known.

IV: RESULTS AND DISCUSSION

The results of the TTI and vitrinite reflectance analysis used for this research are as follow:

A: Lopatin's Method of Predicting Hydrocarbon Maturity

Implementation of Lopatin's method begins with a reconstruction of the depositional and tectonic history of the geological section of interest. This is best accomplished by plotting depth of burial versus geological age and to specify its temperature history.The burial – history curve of the eastern Niger Delta sedimentary basin was plotted from the thermal subsidence and the decompacted depth curves of the basin. The result is shown in Figure 3. In the basin, sediment has accumulated continuously but at varying rates since deposition. The burial history was constructed for the oldest rock unit. All of the shallower and younger horizons burial history is then constructed with their depth – timelines sub-parallel with the first line. A set of these lines forms Lopatin's geologic reconstruction.

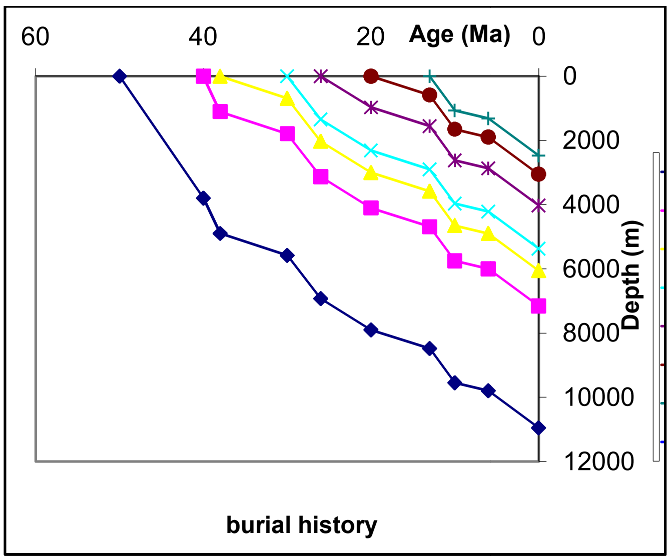

Figure 3: Burial history of the Studied Area

B. Temperature History

The second aspect of the geologic model is to provide temperature history to accompany the burial history curve. The subsurface temperature was specified for every depth throughout the relevant geologic past. Another method was to compute the present-day geothermal gradient (ie 25 ^{0}C/km) for the basin, and assume that both the gradient and surface temperature (ie 27 ^{0}C) have remained constant through the rock history.The temperature history of the basin is constructed as follows. The subsurface temperature is specified for every depth throughout the time interval covered by the reconstruction. Using these data (surface temperature and geothermal gradient) and extrapolating them into the past, we then construct the temperature grid with equally spaced isotherms (10 ^{0}C) parallel to the earth's surface as shown in Figure 4.

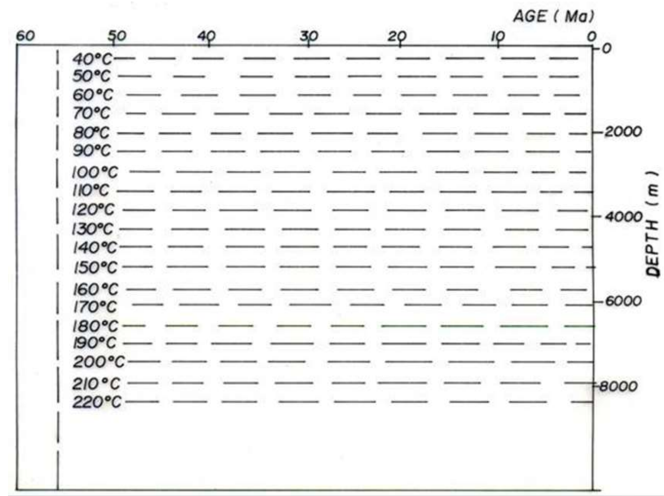

Figure 4: Subsurface-temperature grid that assumes a constant surface temperature (270C) and geothermal gradient (250C/Km) during the last 50my. Isotherms are spaced every 100C for convenience in calculating hydrocarbon maturity.

C: Calculation of Maturity

Theburial – history curves and temperature grids were pasted togetherto obtain Figure 5. The intersections of the burial history curve with each isothermare then marked with dots. These dots defined the time and temperature intervals that were used in the calculations.

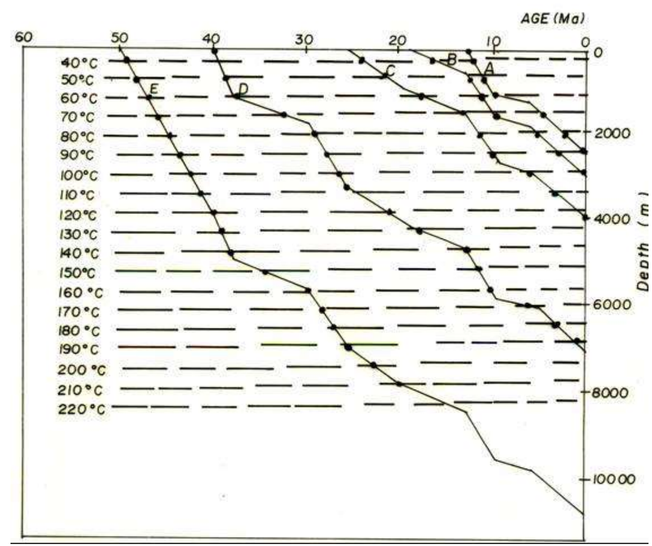

Fig. 5: Geologic model for horizons A, B, C, D, and E.

The computed total thermal maturity values of five horizons; A, B, C, D, and E in the basin using equation 1 are shown in Tables 2. The results show that horizons A and B are immature (TTI < 15). This means that they do not generate hydrocarbon. Horizon C has just attained the maturity level (TTI ≈ 15). Therefore horizon C is oil generating. Horizon D and E are mature and are both oil (TTI > 150) and gas (TTI >165) producing.

Table 2: Calculated Hydrocarbon MaturityHorizon A (13MA)

Temp. interval	Index value	Temp. Factor	Time factor.	TTI	Total
30-40	-7	1/128 = 0.0008	1	0.008	0.008
40-50	-6	1/64 = 0.016	1.2	0.0192	0.02712
50-60	-5	1/32 = 0.03	5.2	0.156	0.1832
60-70	-4	1/16 = 0.06	2.4	0.144	0.3272
70-80	-3	0.13	2.1	0.273	0.6002

Horizon B (20MA)

Temp. interval	Index value	Temp. Factor	Time fat.	TTI	Total
30-40	-7	1/128 = 0.008	5	0.04	0.04
40-50	-6	1/64 = 0.016	1.0	0.016	0.056
50-60	-5	1/32 = 0.03	1.0	0.03	0.086
60-70	-4	1/16 = 0.06	4.2	0.252	0.338
7.-80	-3	1/8 = 0.13	2	0.26	0.598
80-90	-2	¼ = 0.25	2.0	0.50	1.098
90-100	-1	½ = 0.5	0.3	0.15	1.248

Horizon C (26 MA)

Temp. interval	Index value	Temp. Factor	Time factor	TTI	Total
40-50	-6	1/128 = 0.0016	2.5	0.04	0.04
50-60	-5	1/64 = 0.03	3.2	0.096	0.136
60-70	-4	1/32 = 0.06	5.2	0.312	0.448
70-80	-3	1/16 = 0.13	1.0	0.13	0.578
80-90	-2	1/8 = 0.25	1.5	0.375	0.953
90-100	-1	¼ = 0.5	4.3	2.15	3.103
100-110	-0	½ = 1	2.9	2.9	6.003
110-120	1	2 = 2	2.1	4.2	10.2
120-130	2	4	1.1	4.4	14.6

Horizons D (40 MA)

Temp. interval	Index value	Temp. Factor	Time factor	TTI	Total
30-40	-7	1/128 = 0.008	1.0	0.008	0.008
40-50	-6	1/64 = 0.016	0.8	0.0128	0.0208
50-60	-5	1/32 = 0.03	6.0	0.18	0.2008
60-70	-4	1/16 = 0.06	3.0	0.18	0.3808
70-80	-3	1/8 = 0.13	1.0	0.13	0.5108
80-90	-2	¼ = 0.25	2.0	0.50	1.0108
90-100	-1	½ = 0.5	2.8	14.0	15.0108
100-110	0	0	2.2	0	15.0108
110-120	1	$2^1 = 2$	3.0	6.0	21.0108
120-130	2	$2^2 = 4$	5.0	24.0	45.0108
130-140	3	$2^3 = 8$	1.0	8.0	53.0108

140-150	4	$2^4 = 16$	2.0	32.0	85.0108
150-160	5	$2^5 = 32$	4.4	140.8	225.8108
160-170	6	$2^6 = 64$	2.2	140.8	366.6108
170-180	7	$2^7 = 128$	2.4	307.2	673.8108
180-190	8	$2^8 = 256$	1.6	409.6	

HORIZON E (50MA)

Temp. interval	Index value	Temp. Factor	Time factor	TTI	Total
30-40	-7	1/128	0.9	0.007	0.007
40-50	-6	1/64	1.1	0.017	0.024
50-60	-5	1/32	1.9	0.06	0.084
60-70	-4	1/16	1	0.063	0.147
70-80	-3	1/8	1.7	0.213	0.36
80-90	-2	¼	1.0	0.25	0.61
90-100	-1	½	1.6	0.8	1.41
100-110	0	$2^0 = 1$	1.7	1.7	3.11
110-120	1	$2^1 = 2$	1	2	5.11
120-130	2	$2^2 = 4$	1.7	6.8	11.91
130-140	3	$2^3 = 8$	1.0	8.0	19.91
140-150	4	$2^4 = 16$	3	48	67.91
150-160	5	$2^5 = 32$	5	160	227.91
160-170	6	$2^6 = 64$	2	128	355.91
170-180	7	$2^7 = 128$	2	256	611.91
180-190	8	$2^8 = 256$	1.0	256	867.91
190 – 200	9	$2^9 = 512$	3.2	1,638.4	2,506.3
200 – 210	10	$2^{10} = 1024$	4	4099	6602.3
210 – 220	11	$2^{11} = 2048$	6	12,288	18,890.3

D: Vitrinite Reflectance Data Analysis

The least-square regression equation 3 was used to predict the vitrinite reflectance of the study area. The predicted vitrinite reflectance is given in Table 3. A plot of the vitrinite reflectance versus depth on a linear /linear scale is shown in Figure 6.

Table 3: Computed Vitrinite Reflectance from Temperature Values

Depth (Km)	Temperature ^{0}C	Vitirinite Reflectance
0.52	40.0	0.354
0.92	50.0	0.39
1.32	60.0	0.43
1.72	70.0	0.47
2.12	80.0	0.52
2.52	90.0	0.57
2.92	100.0	0.63

Immature

3.32	110.0	0.69	Oil and Gas generation
3.72	120.0	0.764	
4.12	130.0	0.84	
4.52	140.0	0.93	Cracking of oil to gas
4.92	150.0	1.02	
5.32	160.0	1.122	Gas condensate zone
5.72	170.0	1.24	

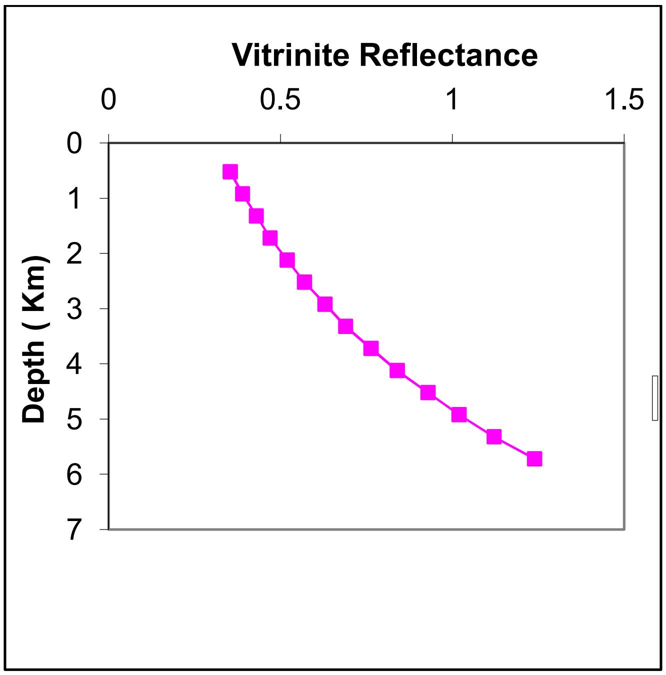

Figure6: Vitrinite Reflectance profile for the eastern Niger Delta

E: Correlation of TTI and Vitrinite Reflectance with stages of Oil Generation

Calculated TTI andvitrinite reflectance values were related to different stages of oil generation and the result is shown in Table 4.

Table 4: Correlation of TTI and R_0 with important stages of oil Generation and Preservation

Stage	**TTI**	**R0**
The onset of oil generation	15	0.65
Peak oil generation	75	1.00
End of oil generation	160	1.30
Upper TTI limit for the occurrence		
Of wet gas	1500	2.2
Last known occurrence of wet gas	65,000	4.8

The result of the thermal maturity for all sediments in the basin indicates that only the sediment of Miocene to Eocene has reached a maturity level for hydrocarbon generation. The high time (age) value may be attributed to the low geothermal gradient of 25^0C km^{-1} used in the calculation. A significant volume of upper Miocene and Paleocene sediments span the whole range of oil and gas generating maturities (TTI > 160). The model shows that hydrocarbon production is taking place above 2000 metres

The vitrinite reflectance increases with depth and the geological age of the basin. The vitrinite reflectance profile shows that the oil window ranges from the depth of 2300 metres to 5000 metres ($0.65 < R_o < 1.0$). A comparison of the TTI values and the Ro values for hydrocarbon generation shows that the two methods give similar results.

The hydrocarbon maturity level of the eastern Niger Delta has been computed from the Temperature Time index of Lopatin and Vitrinite reflectance. The results show that the hydrocarbon level is mature and thus the generation of oil and gas. The results of the thermal maturity indicate that only the sediment of Miocene to Eocene has reached a maturity level for hydrocarbon generation. The hydrocarbon maturity values obtained in this work will provide some incentives for drilling in areas still unexplored and will encourage deeper drilling prospects.The two methods are simple and they complement each other. The maximum vitrinite reflector is 1.24 at a depth of 5.72.

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