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Research Paper

Thermal History Calculation of Niger Delta Sedimentary Basin, Nigeria

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ABSTRACT: *The thermal history of parts of the Niger Delta has been estimated using a thermal model which has been widely applied to estimate the temperature structure of oceanic lithosphere. The data used are the burial history, surface temperature, and thermal conductivity of the study area and some other physical properties. It was assumed that subsidence of the basin started about 60 million years ago. The results show that sediments deposited 2Ma, 5 Ma, 10Ma, 20Ma and 40 Ma after the initiation of subsidence has attained maximum depths of 9807.8m, 8534.83m, 7100.13m,5071.16m and 2201.77 m respectively while their maximum temperatures are approximately 220.22, 195.14, 166.87, 126.90 and 70.37°C respectively. The computed temperature history increases linearly with depth and age of the sediments. The estimated geothermal gradient and heat flow of the basin, obtained from the calculated temperature and depth decreases exponentially with the geological age of the formations. Comparism of the modeled temperatures with that obtained from measured bottom hole temperatures agree favourably. Similarly the computed geothermal gradient and heat flow values also agree with those obtained from the bottom hole temperatures. The thermal history values show that the basin is thermally mature and this is confirmed by the hydrocarbon exploration and production going on in the Niger Delta.*

KEYWORDS: *Thermal history, heat flow, subsidence, sedimentary basin, Niger Delta*

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I. INTRODUCTION

The origin of sedimentary basin depends on how relief is created on the Earth. Basin relief can be formed in two very ways: thermally or flexurally. Thermally, if the lithosphere is heated from below, it expands and becomes less dense and float higher in the asthenosphere due to isostasy thereby producing crustal uplift. If erosion and extensional thinning of the lithosphere accompanies the heating, then, upon re-cooling, the elevation of the top of the lithosphere is less than before the heating and extension, thereby creating a basin for filling by sediments [1, 2].

Heat is very essential in sedimentary basin formation and hydrocarbon generation modeling, therefore reconstruction of the temperature history of any sedimentary basin is important when evaluating petroleum system prospects. Knowledge of the thermal history of a sedimentary basin is very important because the thermal maturation and the generation of hydrocarbon from the source rocks depends on temperature. The major sources of the subsurface heat flow are the earth's core and radioactive elements in the sediments [3, 4]. The burial history of the basin heat flows, thermal conductivity and other inputs are needed for the reconstruction of the thermal evolution of a sedimentary basin.

Subsidence in the sedimentary basin causes sediment deposited at low temperatures to be subjected to higher temperatures with time [5,6]. The cooling of the lithosphere causes subsidence by isostasy. This subsidence results in the formation of ocean basins. In some cases the subsiding lithosphere is covered with sediments. Paleo-temperatureis controlled not only by the basal heat flow, but also by thermal conductivities, heat generation from radioactive sources within the sediments, and regional water flow through aquifers.

The thermal history of a basin can be obtained from the empirical deduction on well logs, samples or by theoretical methods. Hydrocarbon maturation indices such as vitrinite reflectance, Thermal Alteration Index (TAI), or concentration of biological markers offer indirect techniques of thermal history modeling. For the theoretical method, a physical model of the earth is assumed for an initial time prior to the basin formation. In this research, the theoretical (mathematical) method will be applied to the eastern parts of the Niger Delta continental basin.

II. GEOLOGICAL SETTING OF NIGER DELTA

The Niger Delta basin is a major hydrocarbon province in Nigeria. Much has been reported about the structures of the Niger Delta as a result of the available geological and geophysical data from the oil companies in the area. Researchers have shown that the Niger Delta sedimentary basin was formed from the thermal contraction of the lithosphere. Figure 1 shows the location of the study area in onshore Niger Delta sedimentary basin, Nigeria, The basin lies within longitudes 5^0 E and 7^0 E, and latitudes 4^0 N and 6^0 N. The basin is very important because of its petroleum systems. The thickness of the sediments ranges between 9 and 12 km.

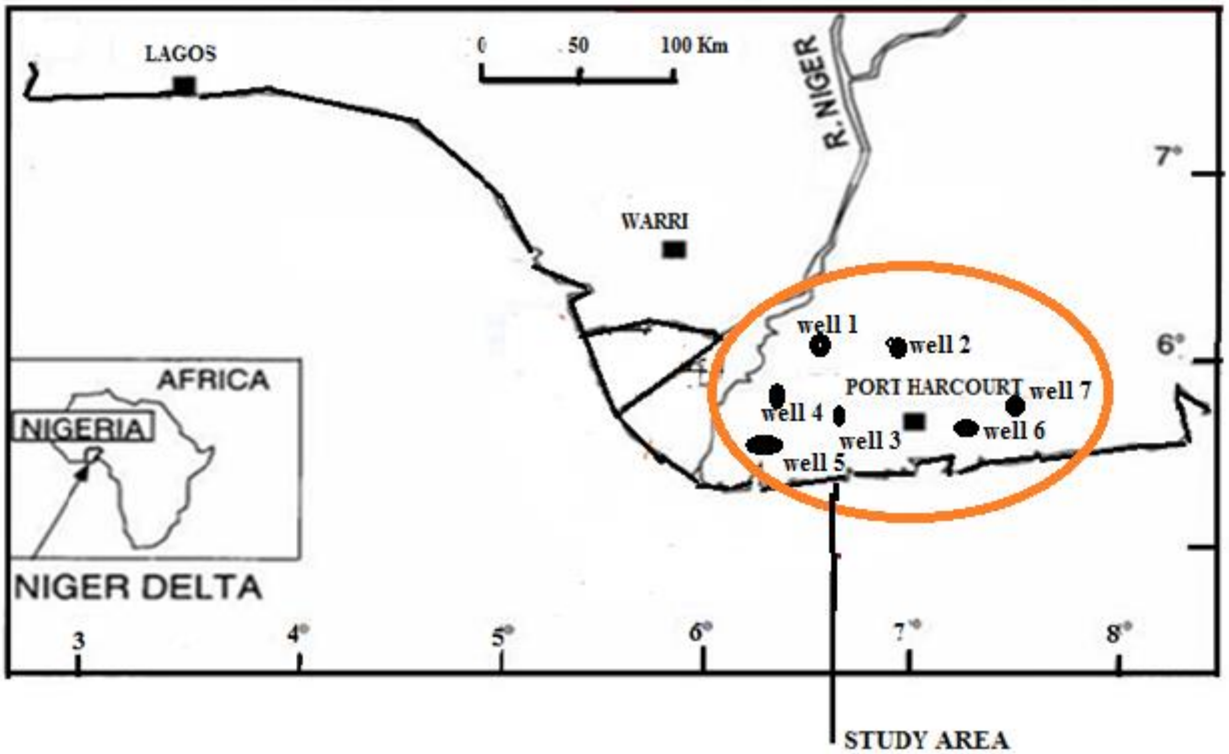


Figure1: Map of Niger Delta showing the study area and some oil well locations

The basin is divided into extensional zone, transition zone, and contraction zone as a result of its tectonic structures. The extensional zone lies on the continental shelf, while the contraction zone lies in the deep-sea part of the basin. The transition zone lies between the extensional and contraction zones. The tectonic structures of the basin are very typical of an extensional rift system, but the added shale diapirism due to compression makes this basin unique. The Niger Delta is divided into three formations - Akata, Agbada and Benin (Figure 2), representing prograding depositional facies that are distinguished mostly on the basis of sand-shale ratios [7, 8, 9, 10].

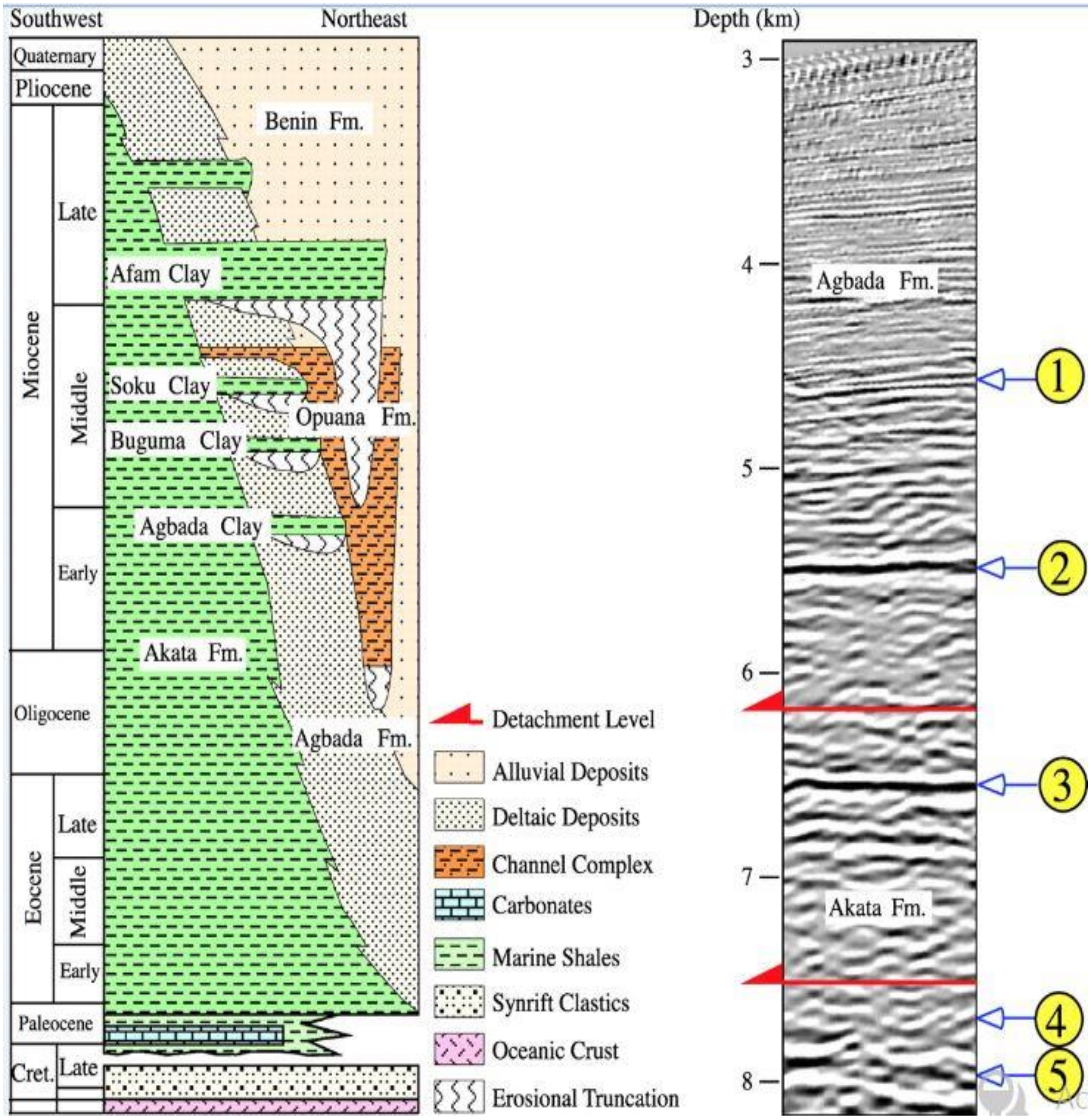


Figure 2: Schematic diagram of the regional stratigraphy of the Niger Delta and variable density seismic display of the main stratigraphic units [11].

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 [12]. The formation is about 7,000 meters thick [9] and underlies the entire delta, and is overpressured. The Agbada Formation, which overlies the Akata Formation, is a major petroleum bearing unit and its deposition began in the Eocene and continues into the Recent. The Agbada formation consists of paralic siliciclastics over 3700 meters thick and represents the actual deltaic portion of the sequence. 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 Benin Formation, a continental deposit of alluvial and upper coastal plain sands that are up to 2000 m thick, overlies the Agbada Formation. The age of the Benin formation ranges from late Eocene to Recent.

III. MATERIALS AND METHODS

Sedimentary basins are formed from the cooling and contraction of the lithosphere [5, 6, 13]. The sedimentary layer transports the heat from the cooling basement rocks to the surface. The thermal history of the sedimentary basin during the subsidence depends on the evolution of the burial depth of the sediments and the rate of temperature change with depth. The heat flux $q_{(s)}$ in the cooling and contracting basin [14, 15] is given as:

$$q_s = \frac{K_m\left(T_m - T_0\right)}{\sqrt{\pi k_m t}} \qquad 1$$

where:

$q_{(s)}$ = heat flux
K_m = thermal conductivity of mantle
k_m = thermal diffusivity of mantle
T_m = temperature of mantle
T_0 = surface temperature
t = time

From Fourier's law of heat conduction, we know that the heat flow in the sediments is given as;

$$q_s = K_s\left(\frac{dT}{dZ}\right) \tag{2}$$

where;

$\frac{dT}{dz}$ = geothermal gradient
K_s = thermal conductivity of sediment
q_s = heat flux

Combining equations 1 and 2, we obtained the geothermal gradient in the cooling /subsiding sedimentary basin as

$$\frac{dT}{dz} = \frac{k_m}{k_s}\frac{\left(T_m - T_0\right)}{\sqrt{\pi k_m t}} \tag{3}$$

The geothermal gradient is the rate of increase in temperature with depth. Assuming a linear relationship between the paleo-temperature and depth of burial, then

$$T = \frac{dT}{dz}(Z_{s(t)}) + T_0 \tag{4}$$

Where;

T	=	temperature
$Z_{s(t)}$	=	depth to sediments deposited at time t_S after initiation of subsidence
$\frac{dT}{dz}$	=	geothermal gradient
T_0	=	surface temperature

Therefore, substituting equation 3 into 4, we obtained the paleo-temperature distribution in the sediment as;

$$T_s = T_0 + \frac{K_m}{K_s}\frac{\left(T_m - T_0\right)}{\sqrt{\pi k_m t}} Z_{s(t)} \tag{5}$$

According to [14, 16] Turcotte and Ahern (1977), and Middleton (1982), the depth Z_S (t) to sediments deposited at time t_S after the initiation of subsidence is:

$$Z_{s(t)} = \frac{2\rho_m \alpha_m \left(T_m - T_0\right)}{\rho_m - \rho_s}\left(\frac{k_m}{\pi}\right)^{1/2}\left(t^{1/2} - t^{1/2}{}_s\right) \tag{6}$$

Therefore, the temperature history of sediment deposited at time t_s at a subsequent time t can be obtained by combining equations 5 and 6 as:

$$T_{SL} = T_0 + \frac{2K_m}{\pi k_s}\frac{\rho_m \alpha_m (T_m - T_0)^2}{(\rho_m - \rho_s)}\left(1 - \sqrt{\frac{t_s}{t}}\right) \tag{7}$$

Where

ρ_s = density of sediment

ρ_m = density of mantle

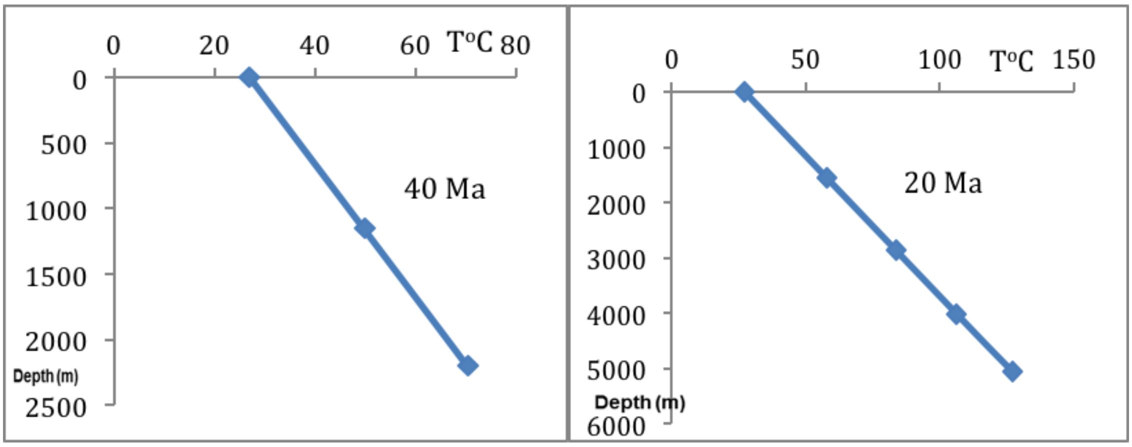
T_m = Temperature of mantle
T_0 = surface temperature
t = age of sediment in million years
k_m = thermal diffusivity of mantle
a_m = volume coefficient of thermal expansion of mantle

IV. RESULTS AND DISCUSSION

The values of the physical parameters used in this study for the calculation are modified from [15, 17, 18, 19] and are shown in Table 1.The temperature of the region over geological time is predicted by putting the physical parameters into Equation 7. It was assumed that subsidence started about 60 million years ago. Figure 3 shows the evolution of the temperature profile versus depth through time over 40 million years, equivalent to the deposition of the basin. It can be inferred from the diagram that sediment deposited 2Ma, 5Ma, 10Ma, 20Ma and 40Ma after the initiation of subsidence has attained maximum depths of 9807.886m, 8534.833m, 7100.134 m, 5071.164m and 2201.766 m respectively while their maximum temperatures are approximately 220.215, 195.14, 166.87, 126.90 and 70.37°C respectively. A maximum temperature of about 300^0C is obtained at a depth of 11,500m (the base of the sediments). From an initial surface temperature of 27 ^{0}C, the temperature of the various sediment units can be obtained from the diagrams. For example sediment deposited 30Ma before present (t_s = 30Ma) would have attained a temperature of about 96.23^0C at a depth of 3514.28m.

Table 1: Physical constants used in calculation

Symbol	Values	Definition
α_m	$3.1 \times 10^{-5}K^{-1}$	Coefficient of thermal expansion
K_m	$10^{-6}m^2/s$	Thermal diffusivity of lithosphere
Ks	$2.1Wm^{-10}C^{-1}$	Thermal conductivity of sediment.
K_m	$1.5Wm^{-1\,0}C^{-1}$	Thermal conductivity of lithosphere
ρ_m	$3260kgm^{-3}$	Density of mantle
ρ_s	$2650kgm^{-3}$	Density of sediment
T_m	1500K	Temperature of mantle
T_0	300K	Surface temperature
$T_m - T_0$	1200K	



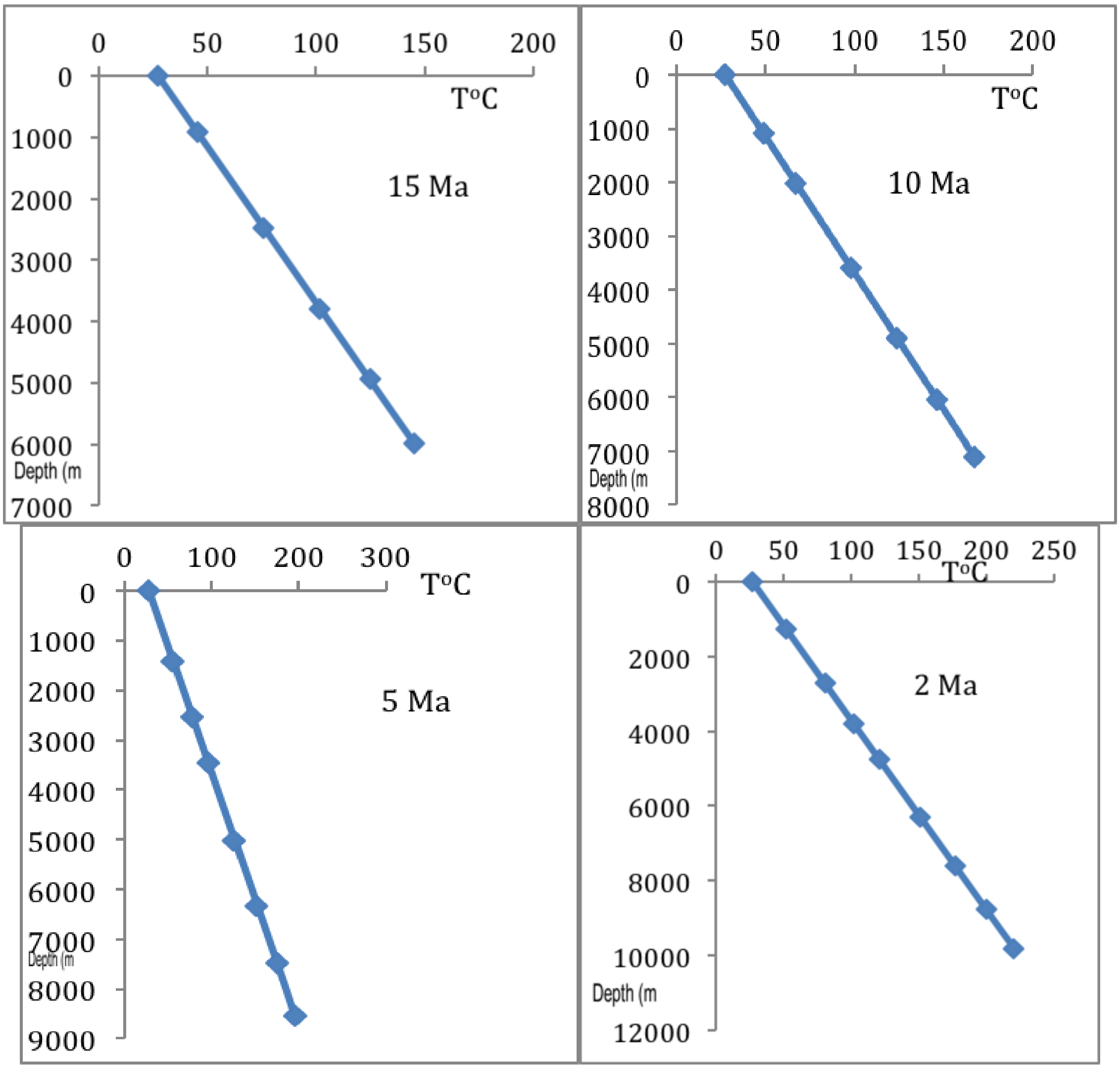


Figure 3: Temperature-depth evolution of sedimentary layers deposited at time ts after subsidence began.

Similarly a temperature of about 65^0C (onset of oil generation) is obtained at a depth of about 2000m for sediments, which were deposited 12Ma before present (t_s = 38). Therefore the oil – liquid window ranges between the depths of 2000 - 5000m within the basin. The thermal history of sediment shows that the subsurface temperature increases with depth and that the surface temperature has remained almost constant throughout the geological period. Similar results were also obtained by other researchers that worked on other parts of the basin ([5, 20].

The heat flow and geothermal gradient of the basin through geological time were also estimated with Equations 1 and 3 respectively. The generated heat flow and geothermal gradients were plotted against the age of the formations in Figures 4 and 5 respectively. The calculated geothermal gradient and heat flow of the basin decreases exponentially with the geological age of the formation. This may be attributed to heat lost to the surface and reduction in the radioactive element in the formation.

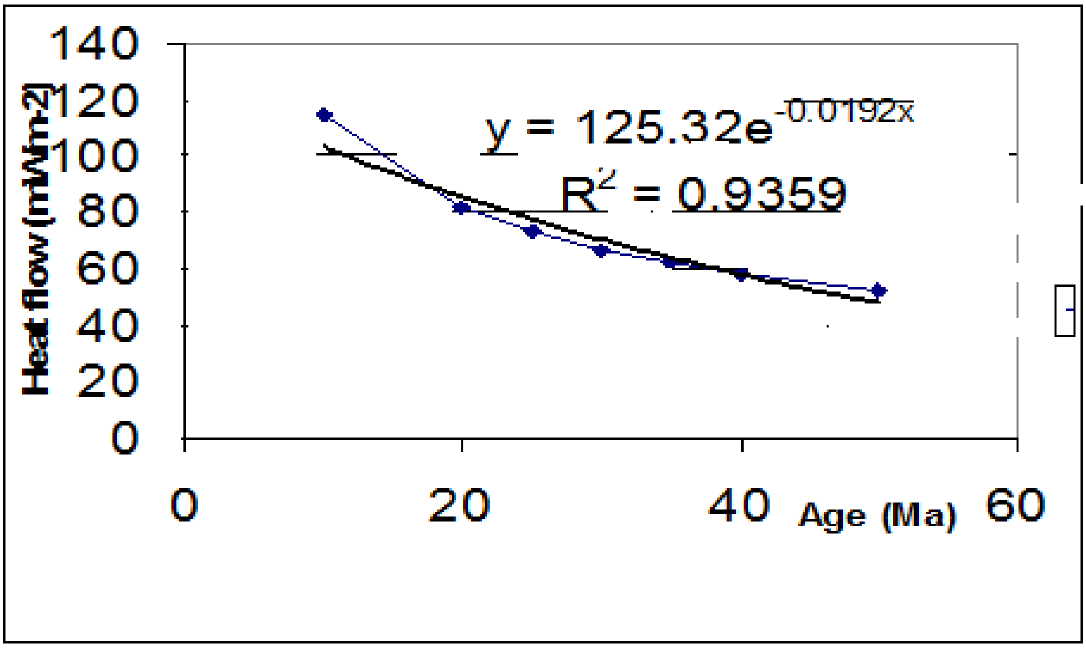


Figure 4: Surface heat flow as a function of time

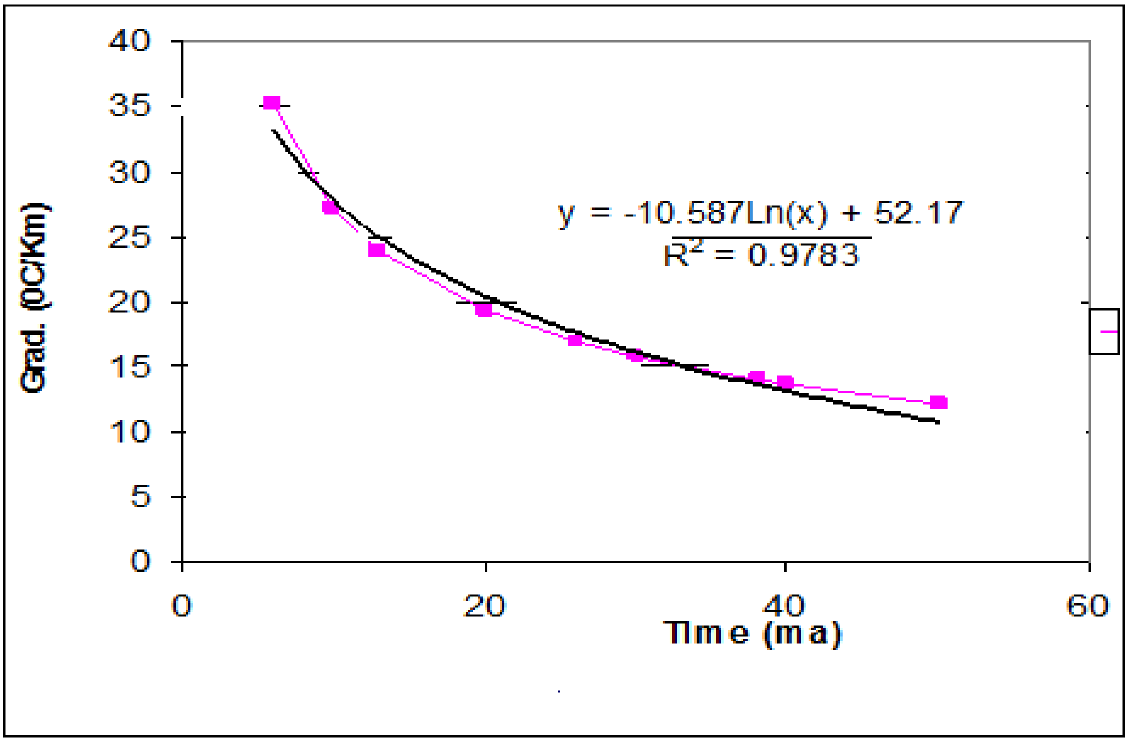


Figure 5: Geothermal gradient as a function of time

The relationship between the geothermal gradient and the geological age of the sediment units is given as

$$Y = -10.587 \ln(X) + 57.17 \qquad 8$$

where,

Y = geothermal gradient ($^0Ckm^{-1}$)

X = geological age in million years.

Similarly, the correlation analysis between the heat flow and the age of the basin is given as,

$$Q = -22.232 \ln(X) + 109.56. \qquad 9$$

Where
Q = heat flow in mWm^{-2}
X =geological age in million years

The correlation coefficients of the geothermal gradient and heat flow with geological age of the basin are 0.9783 and 0.9783 respectively.

The calculated temperature, geothermal gradient and heat flow were compared with measured bottom hole, and geothermal gradient and heat flow from seven oil wells in the study area (Tables 2-8). Column 2 of the tables shows the corrected bottom hole temperatures. The results show that the calculated values of the temperatures with depth are comparable to the measured values for all the wells. The measured temperature increase linearly with depth. Similarly, the computed geothermal gradient and heat flows from the bottom hole temperature are also almost the same as those obtained from the analytical techniques. The results show that the temperature, geothermal gradient and heat flow can be estimated from the analytical equations with confidence.

Table 2: Bottom hole temperature and computed geothermal gradient and heat flow for well 1

Well1 DEPTH(m)	TEMP.(^{O}C)	GRADIENT ($^{O}C/Km$)	HEAT FLOW(m W/m^2)
2101.0	53.8	12.6	15.75
2108.8	54.95	13.2	14.81
2111.2	56.0	13.2	14.12
2169.9	57.3	13.4	15.14
2175.3	58.0	13.4	15.59
2478	57.6	12.0	19.68
2924	69.9	14.6	28.62
2940.5	73.3	15.6	32.45
AVERAGE		13.46	19.52

Table 3: Bottom hole temperature and computed geothermal gradient and heat flow for well 2

Well2 DEPTH(m)	TEMP. (^{O}C)	GRADIENT ($^{O}C/Km$)	HEAT FLOW(m W/m2)
2035.3	67.0	19.0	26.22
2064.0	68.0	20.0	37.4
2227.0	71.4	19.8	40.0
2326.4	75.7	21.0	29.19
2399.0	77.0	20.1	30.15
2433.2	78.0	20.1	37.60
2716.41	82.3	20.3	40.19
2815.0	84.9	20.5	40.80
AVERAGE		20.09	35.16

Table 4: Bottom hole temperature and computed geothermal gradient and heat flow for well 3

WELL 3 DEPTH(m)	TEMP. (^{O}C)	GRADIENT ($^{O}C/Km$)	HEAT FLOW(m W/m^2)
3636.34	98.0	19.7	56.74
3650.96	98.0	19.3	56.74
3736.25	101.0	19.8	55.44
3856.28	103.5	19.7	57.13
3911.41	103.9	19.6	60.96
4070.4	107.3	19.5	65.72
4157.69	111.0	20.0	58.4
4229.3	113.0	20.3	64.15
4336.93	118.8	20.8	63.02
AVERAGE		19.86	59.81

Table 5: Bottom hole temperature and computed geothermal gradient and heat flow for well 4

Well 4 DEPTH(m)	TEMP. (^{O}C)	GRADIENT (^{O}C/Km)	HEATFLOW (m W/m2)
2592.66	64.9	14.6	29.05
2799.00	70.5	15.6	32.92
3117.67	79.4	16.7	41.42
3126.85	82.3	17.1	40.53
3319.38	88.5	18.3	40.26
3668.38	100.3	19.8	57.02
3745.36	103.4	20.3	51.97
4222.9	115.3	20.8	60.32
AVERAGE		17.90	44.19

Table 6: Bottom hole temperature and computed geothermal gradient and heat flow for well 5

Well 5 DEPTH (m)	TEMP. (^{O}C)	GRADIENT (^{O}C/Km)	HEAT FLOW (m W/m^2)
173.15	79.7	44.0	47.52
1295.89	82.0	42.0	44.94
1418.8	83.0	40.0	61.2
1968.23	91.8	32.0	46.4
2302.97	96.3	29.8	59.0
2395.5	98.2	29.2	57.82
2401.89	98.3	29.3	63.0
2545.5	101.0	28.6	65.49
AVERAGE		34.36	55.67

Table 7: Bottom hole temperature and computed geothermal gradient and heat flow for well 6

Well 6 DEPTH(m)	TEMP. (^{O}C)	GRADIENT (^{O}C/Km)	HEAT FLOW(m W/m^2)
1884.9	84.3	29.8	21.16
1917.94	84.8	29.9	51.43
2014.22	88.0	29.7	63.6
2308.12	94.6	28.9	54.62
AVERAGE		29.58	47.70

Table 8: Bottom hole temperature and computed geothermal gradient and heat flow for well 7

Well 8 DEPTH (m)	TEMP. (^{O}C)	GRADIENT (^{O}C/Km)	HEAT FLOW(mW /m^2)
221.5	75.8	15.0	30.9
3227.78	76.5	15.2	30.25
3323.0	78.0	15.2	37.39
3482.8	83.0	16.0	44.32
3537.8	85.5	16.4	39.36
3684.62	92.0	17.5	44.45
AVERAGE		15.88	37.78

V. CONCLUSION

The theoretical modeling of the thermal history of parts of the Niger Delta basin has shown that the result can be used in determining the hydrocarbon maturity and generation. The modeling shows linear temperature-depth evolution of the sedimentary layers deposited at time ts after subsidence began. The research also shows a natural logarithm relation between the heat flow and geothermal gradient with depth. The method is simple and can be applied to the deep-sea region of the basin where hydrocarbon exploration is currently on.

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