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One-dimensional Geotemperature Modeling Using One-layer Model for Awa Oil Field, Niger Delta Sedimentary Basin, Nigeria Using One Layer Model

Emujakporue Godwin Omokenu[1*]

[1]Department of Physics, University of Port Harcourt, Nigeria.

Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

In this research, one-dimensional steady state thermal structure in part of Niger Delta sedimentary basin has been modelled using one layer model. The solution to the Fourier one dimensional heat flow was used to generate geotherm the area. The model column is about 7.0 Km thick, has average thermal conductivity and radioactive heat generation of 2.5 Wm^{-1} C^{-1}, and 2.0 μWm^{-3} respectively. Two boundary conditions; surface temperature and heat flow of 27°C and $50mWm^2$ were also used. The computed temperatures using the model increases with depth from earth surface to about 6500 metres. Beyond 6500 metres, the temperature starts decreasing with depth as a result of the quadratic nature of the model. The depth range within which the temperature increases with depth falls within the Benin and Agbada Formations of the Niger Delta. Comparison between the computed temperature and measured bottom hole temperature from three wells reveal a very good matched. The diference between computed and measured temperature ranges between -4.0 to 6.0°C. The thermal structure of the sedimentary basin is controlled by thermal conductivity and radiogenic heat production.

Keywords: Geotherm; analytical modeling; thermal conductivity; bottom hole temperature; heat flow.

**Corresponding author: E-mail: owin2009@yahoo.com;*

1. INTRODUCTION

The earth is continuously losing heat to the atmosphere as a result of the earth's cooling and the decay of radioactive elements. The heat from the subsurface is responsible for mantle convection, plate tectonics, mountain building and thermal maturation of hydrocarbon [1]. Due to the important of geothermal status, considerable attention has been directed toward the study and understanding of the variation in the subsurface temperature field in space and time [2]. The primary observable quantity for heat flow is the temperature gradient, which is in turn is used to estimate the flow of heat from the earth's interior and hence draw inferences about the thermal structure and evolution of the subsurface.

The earth is made up of the core, mantle and crust. The earth crust is the topmost layer and it is solid in nature. The mantle lies in between the crust and the core and it is fluid in nature. The core which is the base of the earth interior is made up of the outer and inner cores. The inner core is solid while the outer core is fluid. Most heat in the earth is generated in the core and transported through the mantle and crust to the earth surface. The heat is usually transported by conduction, convection and radiation. Heat conduction is the major technique in the earth crust while convectional method is common in the mantle [3].

Sedimentary basin lies on top of the earth crust and the temperature in the basin is control partly by activities beneath the basin. The temperature is the physical property which determine the direction of heat flow. The geotemperature usually increases with depth and as a result heat flow from the earth's interior to the surface [4]. An understanding of the subsurface temperature can be used in detecting direction of fluid flow and subsurface pressure, determination of hydrocarbon source maturity and basin modelling. Temperature–depth profiles within the Earth are called geotherms. The aim of this work is to model one dimensional temperature equation for part of the Niger Delta sedimentary basin.

Fig. 1 is a map of the Niger Delta showing the study area. The Niger Delta is the youngest sedimentary basin within the Benue Trough system and its development started after the Eocene tectonic phase [5,6]. The thickness of the Niger Delta sediment is about 12 Km and the main supplier of sediments are River Niger and River Benue.

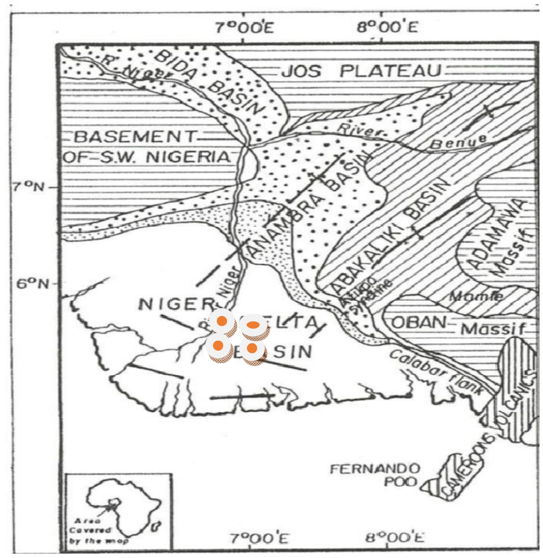

Fig. 1. Map of Niger Delta showing location of wells

The lithostratigraphy of the Niger Delta is divided into three Formations (Fig. 2) representing prograding depositional facies that are distinguished based on sand – shale ratios. The Formations are Benin, Agbada and Akata Formations [7]. The Benin Formation is the youngest of the Delta sequence and it consists mainly of sand and gravels with thickness ranging from 0 – 2100 metres. The sands and sandstones in this Formation are coarse – fine, granular in texture and partly unconsolidated. The Benin Formation contains mainly feldspars, hemalites, lignite streak and limonite coatings. Little oil has been discovered in the Benin formation, and the formation is mainly water bearing. It is the major source of portable water in the Delta area [6].

The Agbada Formation consists of alternation of sandstones and shale and it lies beneath the Benin Formation. The shale and sandstone were deposited in equal proportions in the lower part of the formation. The deposition of Agbada Formation began in Eocene and continues into Pleistocene. The thickness of the Agbada Formation ranges from 300 m – 4500 m (Short and it is the major host of Niger Delta hydrocarbon.

The Akata Formation forms the base of the transgressive Delta complex. It is of marine origin

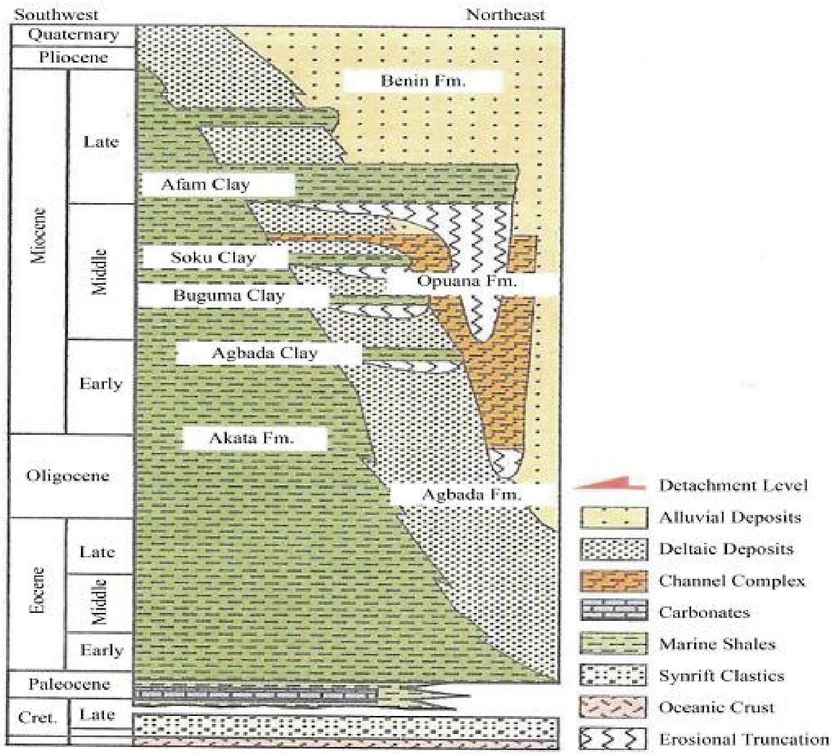

Fig. 2. Stratigraphic setting of Niger Delta showing the three formations of Niger Delta [modified after 6]

and it consists of thick shale sequence (potential source rock), turbidite sand (potential reservoir in deep water) and small amount of clay and silt [8]. The Akata Formation was formed when terrestrial organic matter and clays were transported to deep water areas characterized by low energy conditions and oxygen deficiency. The thickness ranges from 0 – 6000 m. The Akata formation outcrops subsea in the outer Delta area but rarely seen onshore. The formation outlies the entire Delta, and it is commonly overpressured.

2. MATERIALS AND METHODS

Heat is a form of energy which flows from a hot region to a cold region. The physical property which determine the direction of heat flow is temperature and the rate at which heat is transported through a solid material is a function of temperature gradient [9-12]. The higher the temperature gradient, the faster the heat flow. Heat flow through sedimentary basins mainly by conduction following the heat flow equation:

$$Q = -\frac{KdT}{dz} \quad (1)$$

Where

K = thermal conductivity of the material
Q = heat flow
dT = change in temperature
dz = change in depth

The negative sign is as a result of heat flow from high to low temperatures. The thermal conductivity is the assumed mean of heat conductivity for all the components in the body. Considering a one-dimensional sedimentary column with no erosion or deposition and a constant heat flow from the earth's interior, the column may eventually reached a steady state of thermal equilibrium in which the temperature at any point is steady. At the thermal equilibrium state, the temperature-depth profile is known as geotherm [13,14,2]. The temperature at the steady state can be obtained by integrating equation 1, to obtained

$$\mathrm{T(z)} = To + \frac{QoZ}{K} \quad (2)$$

Where

T(z) = Temperature at depth z
To = Surface temperature
Qo = surface heat flow

The total heat flow in the sediment is due to radioactive heat production in the sediment and heat flow from the interior of the earth. The steady state temperature equation in the sedimentary column when heat is produced in the column by radioactive elements is given as

$$\frac{\partial^2 T}{\partial z^2} = \frac{A}{K} \quad (3)$$

Where

A = Heat production in the sediment (mWm−3),
K = Thermal conductivity (Wm−1 °C)
T= Tempertature (°C)
Z= depth (m)

Equation 3 is a second order differential equation and it can be solved to obtain the temperature by integrating the equation twice. The solution of the equation require two boundary conditions. One of the boundary condition is a constant temperature or heat flow at the surface and the other one is the temperature or heat flow at the base of the sediment column. Integrating equation 3, we obtain

$$Q = \frac{\partial T}{\partial z} = \frac{AZ}{\mathrm{K}} + C1 \quad (4)$$

In order to obtain the equation for T, the following two boundary conditions were applied;

(a) Temperature $T = 27oC\ at\ Z = 0\ Km$

And

Surface heat flow Surface heat flow $Q = -\frac{K\partial T}{\partial z} = -\mathrm{Qo}\ \ at\ z = 0$

The surface temperature in the study area is 27°C [15]. The surface heat flow Q = −Q0 is negative because heat flows upwards out of the subsurface, which is in the negative z direction. Applying the second boundary condition to equation 4, then

$$C1 = \frac{Qo}{k} \quad (5)$$

Substituting equation 5 into equation 4, we obtain

$$Q = \frac{\partial T}{\partial z} = -\frac{AZ}{K} + \frac{Qo}{K} \quad (6)$$

Integrating equation 6, then

$$T = -\frac{AZ^2}{2K} + \frac{QoZ}{K} + C2 \quad (7)$$

Applying the first boundary condition to equation 7, then

$$\mathrm{C2} = 27\mathrm{oC} \quad (8)$$

Therefore, putting equation 8 into 7, then

$$T = -\frac{AZ^2}{2K} + \frac{QoZ}{K} + 27 \quad (9)$$

In this work, the geotherm of the study area will be computed based on surface internal observations. The observations are surface heat flow, heat production in the sediment and thickness of the sediment. Equation 9 was used for estimating the vertical variation of subsurface temperature distribution in the studied region. The model assumed that the studied area is made up of one layer (one-layer model). The computed geotherm was compared with bottom hole temperatures from three wells in the Awa oil Field. The temperature data used for the study were obtained from Shell Petroleum Development Company. Temperature measurements are made at the bottom of the well and sometimes at intervals up the well. The temperature sensors were attached to most tools that were run in the wells for the measurement of the maximum temperature. Readings from a number of the maximum thermometers attached to different tool combinations and run at different times were analyzed to give the bottom hole temperature, BHT.

3. RESULTS AND DISCUSSION

Many researchers have computed the geothermal gradient and heat flow of the Niger Delta [10,11]. The average surface heat flow and temperature are 50 Wm-2 and 27°C respectively. The average radiogenic heat production is about 2.0 µWm-3 [16]. These values were used in equation 9 to estimate the temperature distribution in the study area. The result of the subsurface temperature distribution is shown in Fig. 3a and 3b.

Fig. 3a is a plot of model temperature versus depth. A polynomial trend with regression coefficient of one (1) was fitted to the curve. The high value of R2 is an indication that the polynomial equation can be used to determine temperature at any given depth (especially for depth less than 7 Km) with confident. The geotherm (Fig. 3b) shows a gradual increase in temperature with depth. Although at greater depths (above 7 Km), there is some challenges in the confidence in the equation because of the polynomial nature of the solution. The depth interval (0-7Km) within which there is confidence in the model falls between the Benin and Agbada Formations in the Niger Delta. The total thick of the two formations is approximately 6-7 Km.

In order to test the accuracy of the model, the computed geotherm was compared with bottom hole temperatures obtained at different depths in some wells in the Awa oil field. The results from three of the wells is shown in Table 1. The measured bottom hole temperature and their corresponding depth for the three wells are shown in columns 3 and 2 respectively. The computed temperature at the various depths using the analytical model (equation 9) is given in column 4. Column 5 of the table is the difference between the measured and computed temperatures. The difference is within tolerance level because it ranges between -2.9 and 6.0.

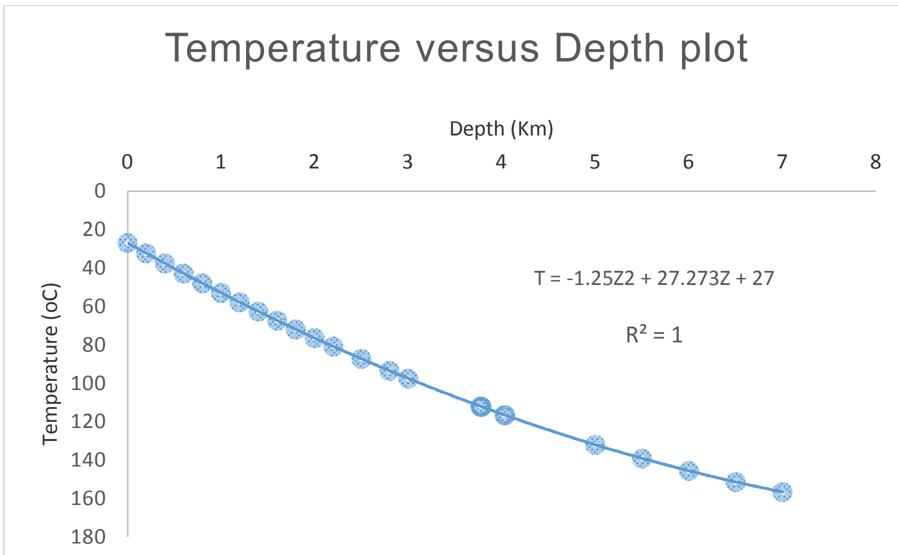

Fig. 3a. Subsurface temperature distribution

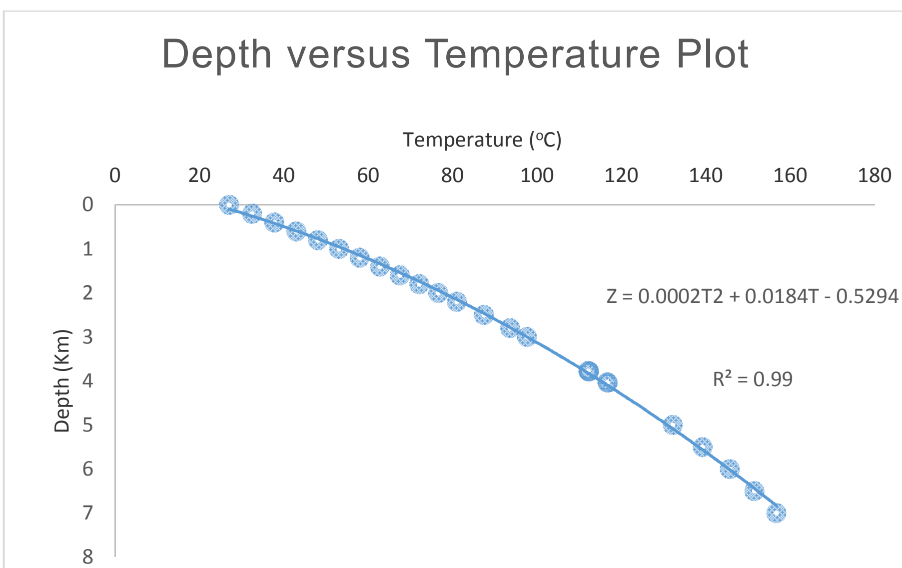

Fig. 3b. Subsurface temperature distribution

Table 1. Measured and computed bottom hole temperature for three wells

Well	Depth (Km)	Bottom hole temp °C	Computed temp °C	(Bot temp-comp. temp)
Well 1	3.218	98.89	101.8192	-2.92923
	3.21716	98.89	101.8031	-2.91308
	3.21564	98.89	101.7738	-2.88385
	3.80634	117.22	112.699	4.521008
	3.80665	117.22	112.7045	4.515503
	3.80695	116.67	112.7098	3.960176
	3.80875	117.22	112.7418	4.478221
Well 2	3.039	97.78	98.33742	-0.55742
	3.051	97.78	98.57334	-0.79334
	3.206	107.22	101.5883	5.631681
	3.330	107.22	103.9571	3.262943
	3.3395	107.22	104.1369	3.083053
	3.205	107.22	101.5691	5.65094
	3.380	111.11	104.9013	6.208682
	3.394	111.11	105.1646	5.945409
	3.390	111.11	105.0894	6.02058
Well 3	2985.2	92.78	97.27527	-4.49527
	2.981	92.78	97.19205	-4.41205
	2.985	92.78	97.27131	-4.49131
	2.980	92.78	97.17223	-4.39223
	3.041	101.67	98.37676	3.293238
	3.044.2	101.67	98.43969	3.230306
	3.176	101.67	101.0095	0.660538
	3.1766	101.67	101.0211	0.648939

Most oil wells drilled in the Niger Delta are within the Benin and Agbada Formations. The maximum depth drilled so far is approximately 4 Km. Therefore the Temperature of the basin for depths more than 4 km can only be obtained by extrapolating the temperature into the subsurface. The result of the difference between the computed temperature and the measured temperature shows that the values are very similar and the model can be trusted and applied in the upper region of the basin especially the Benin and Agbada Formations. The major limitation of the model is its polynomial nature which is responsible for the reversal of the temperature at greater depth.

4. CONCLUSION

In this paper, the 1-D steady-state heat conduction equation for one layer model has been solved and applied to part of the Niger Delta sedimentary basin. The techniques presented have helped in obtaining exact analytical solutions for the Fourier one dimensional heat flow. Comparing the temperature generated with the solution to the temperature obtained from bottom hole temperature of three wells shows that the solution give a good match. The computed temperature structure provides useful information on the thermal state of a sedimentary basin.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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