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# Analytical Determination of Subsurface Temperature using Two Layers Model in Part of Niger Delta Sedimentary Basin, Nigeria

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## I. Introduction

Geothermal heat flow is a natural process by which heat is transferred from the earth interior to the surface. Heat can be transferred by three different ways, namely conduction, convection, and radiation (Cacace et al., 2010; Beardemore and Cull, 2001).Conduction is the major process by which heat is transfer through the solid part of the earth (crust) while in the fluid part (mantle) heat is usually transfer by convectional method. Geothermal heat flow variation is dependent on subsurface temperature variation and distribution, rock thermal conductivity and depths to heat sources.

Some researchers have worked on the geothermal gradient and heat flow of different parts of the Niger Delta sedimentary basin using bottom-hole or continuous temperatures. Two of the researchers (Odumodu and Ayonma, 2014) calculated the geothermal gradient and heat flow in parts of the eastern Niger delta from bottom hole temperature in 71 wells and obtained geothermal gradient varying between 12 to 24°C/Km with an average of 17.6°C/Km in the coastal swamp, 14°C /Km to 26°C/Km with an average of 20.4 $^{O}$C/Km in the shallow offshore. They obtained average heat flow value of 42.5mWm$^{-2}$. Another group (Chukwueke et al., 1992) discovered that the geothermal gradients and heat flow values in the distal part of the Niger delta varies between 19-32$^{O}$C/Km and 45-85mWm$^{-2}$ respectively.

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The major source of information about subsurface temperature is from continuous or bottom hole temperatures measured in oil wells(Rider, 2002). Unfortunately, as a result of high cost and limited depth of drilling, current drilling campaigns in the Niger delta are limited to depths of only a few kilometres and at certain places, rendering direct and complete characterization of the entire subsurface thermal regime impossible to be carried out. Therefore, it is imperative to predict subsurface thermal conditions using alternative means. One method, is by solving Fourier's 1-D steady- state conduction heat flow equation for various layer models and applying it to a given basin.

A steady-state heat flow occurs when the amount of heat arriving and leaving a column of substance is equal over long period of time. Heat conduction across unit area, is a function of thermal property of the material and thermal conductivity. The ability of a substance to transfer its internal heat from one point to another depends on its thermal conductivity(Turcotte and Schubber, 2002; Safanda, 1985; Rudnick et al., 1998). The basin model is based on an extensional sedimentary basin where heat transfer by conduction dominates and the effect of advective transfer of heat by circulating groundwater is negligible due to flat surface topography. The spatial variation of temperature of a sedimentary basin is dependent on thermal conductivity, boundary conditions, water flow, rate of sedimentation and erosion and radiogenicheat production.

The objective of this research is to perform analytical modelling of 1-D conductive steady state temperature distribution of part of the Niger Delta by using two layer techniques and to characterize the geothermal features of the subsurface. The analytical solution of the 1-D Fourier heat flow for two layers model will be used to compute the subsurface temperature of the study area which will be compared with measured temperature from some oil wells.

## II. Summary of the Geology of the Niger Delta

Figure 1 shows the location of the study area within the Niger Delta sedimentary basin. The Niger Delta is the youngest sedimentary basin in the Benue

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Trough system and it started developing after the Eocene tectonic phase (Ekweozor and Daukoru, 1994; Doust and Omatsola, 1990). The Niger and Benue Rivers is the main supplier of sediments. The thickness of the sediment is approximately 12.0 Km.

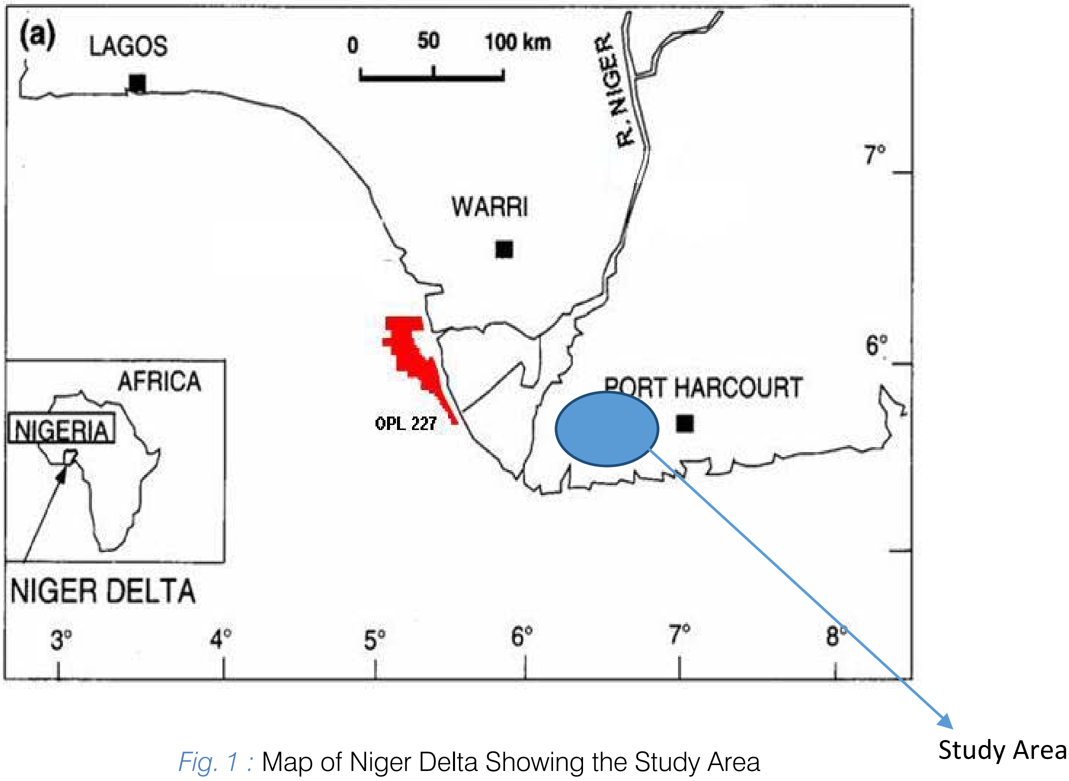


*Fig. 1 :* Map of Niger Delta Showing the Study Area

The Tertiary portion of Niger Delta is divided into three lithostratigraphy (Figure 2.) representing prograding depositional facies that are distinguished based on sand – shale ratios. The lithostratigraphyare Benin, Agbada and Akata Formations(Ekweozor and Omatsola, 1994; Kulke, 1995). The Benin Formation is the youngest of the Delta sequence and it consists mainly of sand and gravels with thickness ranging from 0 - 2100m. The sands and sandstones in this Formation are coarse – fine and commonly granular in texture and partly unconsolidated. Very little oil has been found in the Benin formation, and it is the major source of portable water in the area.

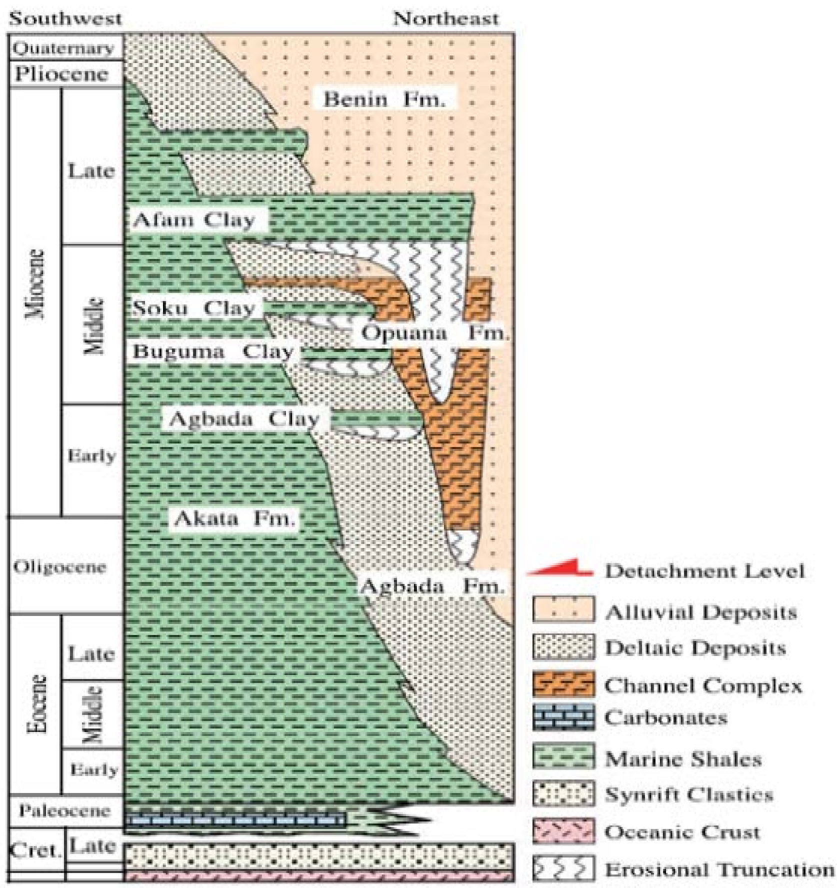


*Fig. 2 :* Stratigraphic setting of Niger Delta showing the three formations of Niger Delta (modified after [1])

The Agbada Formation consists of alternation of sandstones and shale. The deposition of Agbada Formation began in Eocene and continues into Pleistocene. Shale and sandstone beds were deposited in equal proportions in the lower portion. The upper portion consists of minor shale interbed. The thickness of the Agbada Formation ranges from 300m – 4500m. Most reservoir in the Niger Delta are found in the Agbada Formation.

The Akata Formation forms the basal part of the Delta complex. It is of marine origin and it is made up of thick shale sequence (potential source rock), turbidite sand (potential reservoir in deep water) and minor amount of clay and silt(Avbovbo, 1978). Beginning in the Paleocene and through the recent, 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 of the Akata Formation ranges from 0 – 6000m. The formation out lies the entire Delta, and is typically over pressured. It is the major source rock in the basin.

## III. Materials and Methods

In order to characterize the process of heat transfer in the subsurface, it is necessary to understand the underlying physical principle. The general conduction equation governing heat transfer in the Earth is the Fourier heat equation (Mussett and Khand, 2000; Lowrie, 2007). The one-dimensional steady state heat conduction equation in vertical direction in a sedimentary column for a two layers model(Fowler, 2005) is given as;

$$\frac{d2T}{dz2} = -\frac{A1}{K} \quad (1)$$

And

$$\frac{d2T}{dz2} = -\frac{A2}{K} \quad (2)$$

Where

$T$ = temperature (°C)

$A\ (1)$ = radioactive heat production for layer 1

$A\ (2)$ = radioactive heat production for layer 2

$K$ = thermal conductivity ($Wm^{-1}$ °C)

$z$ = depth (m).

The radioactive heat production is as expressed as source ($mWm^{-3}$). The assumed two layers are the Benin and Agbada Formations of Niger Delta sedimentary basin. Assuming the heat production in the Benin and Agbada Formations are A1 and A2 respectively and the boundary between the two lithostratigraphy is Z1, then the ordinary differential equations 1 and 2 can be solved by applying the following assumptions and boundary conditions:

*Assumptions*

A = A1 for 0 ≤ z < z1 (Benin Formation) (3)

A = A2 for z1 ≤ z < z2 (Agbada Formation) (4)

Boundary Conditions

T = 27°C on z = 0 (5)

Q = −Q2 on z = z2. (6)

Where

*Q2* = heat flow from the base of the Agbada Formation.

The average surface temperature in the Niger Delta is 27°C. The basal heat flow Q=−Q2 is negative because heat flow upwards out of the earth, which is in the negative z direction. It is straightforward to solve the second order temperature differential equations (1 and 2) with two integrations. Integrating the differential equations two times results in two integration constants. The constants can be obtained by applying the two boundary conditions(Stein, 1995; Gibson, 2008). Integrating equations (1 and 2) once, we obtained

$$\frac{dT}{dz} = -\frac{A1}{K}z + C1 \quad (7)$$

And

$$\frac{dT}{dz} = -\frac{A2}{K}z + c2 \quad (8)$$

Integrating equations 7 and 8, then

$$T1 = -\frac{A1Z2}{K} + C1Z + C3 \quad (9)$$

And

$$T2 = -\frac{A2Z2}{K} + C2Z + C4 \quad (10)$$

Where T1 and T2 are the temperature regimes of Benin and Agbada Formations respectively. Applying the first boundary condition (equation 5) to equation 9, at the earth surface, then

$$C3 = 27 \quad (11)$$

Equation 7 is equal to equation 8 at the boundary between the two layers (Z1), therefore

$$-\frac{A1}{K}z1 + C1 = -\frac{A2}{K}z1 + c2 \quad (12)$$

Solving for C1 in terms of C2, then

$$C1 = -\frac{A2}{K}z1 + \frac{A1}{K}z1 + c2 \quad (13)$$

Putting equation 13 into equation 9, we have

$$T1 = -\frac{A1Z2}{K} + \left(-\frac{A2}{K}z1 + \frac{A1}{K}z1 + c2\right)Z + C3 \quad (14)$$

Substituting equation 11 into equation 14, we obtained

$$T1 = -\frac{A1Z2}{K} + \left(-\frac{A2}{K}z1 + \frac{A1}{K}z1 + c2\right)Z + 27 \quad (15)$$

At the base of the Agbada Formation (Z= Z2), applying second boundary condition (equation 5);

$$\frac{dT}{dZ} = \frac{Q2}{K} \quad (16)$$

Comparing equations 8 and 16, then

$$\frac{Q2}{K} = -\frac{A2}{K}z2 + c2 \quad (17)$$

Solving for C2 in equation 17, we obtained

$$c2 = \frac{A2}{K}z2 + \frac{Q2}{K} \quad (18)$$

Substituting equation 18 for C2 in equation 15, we obtained

$$T1 = -\frac{A1Z2}{K} + (-\frac{A2}{K}z1 + \frac{A1}{K}z\ 1 + \frac{A2}{K}z2 + \frac{Q2}{K})Z + 27 \quad (19)$$

Similarly, putting equation 18 into 10, we obtained

$$T2 = -\frac{A2Z2}{K} + (\frac{A2}{K}z2 + \frac{Q2}{K})Z + C4 \quad (20)$$

At z1, equation 19 is equal to equation 20, therefore

$$-\frac{A2Z2}{K} + \left(\frac{A2}{K}z2 + \frac{Q2}{K}\right)Z1 + C4 = \frac{A1Z2}{K} + \left(-\frac{A2}{K}z1 + \frac{A1}{K}z1 + \frac{A2}{K}z2 + \frac{Q2}{K}\right)Z1 + 27 \quad (21)$$

Solving for C4, we have

$$C4 = \frac{A1Z2}{K} + \frac{A2Z2}{K} + \left(-\frac{A2}{K}z1 + \frac{A1}{K}z1\right)Z1 + 27 \quad (22)$$

Putting equation 22 into equation 20, we have

$$T2 = -\frac{A2Z2}{K} + \left(\frac{A2}{K}z2 + \frac{Q2}{K}\right)Z + \frac{A1Z2}{K} - \frac{A2Z2}{K} + \left(-\frac{A2}{K}z1 + \frac{A1}{K}z1\right)Z1 + 27 \quad (23)$$

The solutions 19 and 23 give the temperature at any position in the depth interval 0 to z1 and z1 to z2.

## IV. Result and Discussion

The equilibrium geotherm for the Benin and Agbada Formations was calculated by considering each layer separately. Figure 3depictsa 1-D model for the two layers with its associated boundary conditions (surface temperature and basal heat flow). Thermal conductivity and heat production are the internal properties that influence the temperature structure in the column. The thermal conductivity and heat production were obtained from well logs (Emujakporue, 2009; Emujakporue, 2016).

The model is made up of sediment column with two layers of thickness 1.8 and 4.5 Km respectively. The thermal boundary conditions are surface temperature To = 27°C and basal heat flow of 50.0mWm$^{-2}$ and thermal conductivity. Temperature and temperature gradient were matched across the boundary between the two layers.

Using the above model properties the equilibrium geotherm was calculated for the two lithostratigraphy from equations 21 and 23. The equilibrium geotherms was calculated by assuming heat production and thermal conductivity for layer 1 to be 1.8*10$^{-6}$ and 2.0 Wm$^{-1}$ °C$^{-1}$respectively. Similarly, for the second layer, basal heat flow, heat production and thermal conductivity were 50 mWm$^{-2}$, 2.1*10$^{-6}$, and 2.2 Wm$^{-1}$°C$^{-1}$.

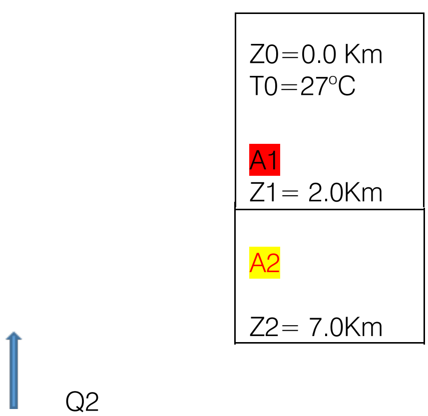


*Fig. 3 :* A two-layer model for the Benin and Agbada Formations

The computed temperature depth distribution is shown in Figure 4. The geotherm increases linearly with depth which is normal. The linear relationship between computed temperature and depth from the graph is given as;

$$T = 22.407x + 27.0 \qquad (24)$$

The regression coefficient for the equation is 0.9992. The high regression coefficient is an indication of the significant and confidence imposed on the relationship. The equilibrium geotherm for the model rock column changes when the conductivity, radioactive heat generation and basal heat flow are varied.

Equation 24 was applied to part of the Niger Delta and compare with measured bottom hole temperature from some oil wells in the Niger Delta and the result is shown in Table 1.The difference between measured and computed temperature ranges between -4.0 to 5. 0°C.The difference between the measured and computed values are minimum and within tolerance level. The computed average geotherm provides an interesting useful information on the thermal state of the sedimentary basin.

As a result of lateral variation of heat flow due to changes in lithology, thermal conductivity, heat production and groundwater flow, it is necessary to carry out accurate determination of the above parameters in order to use the model equations. The results of the geothermal modelling can be used as an aid to interpreting heat flow patterns in the study area, thermal and hydrocarbon modelling. The surface heat flow can be calculated by multiplying the temperature gradient (slope of the graph) with the thermal conductivity values at a particular depth. Therefore, accurate geothermal heat flow is dependent on accurate determination of subsurface lithology distribution and their corresponding thermal conductivity values.

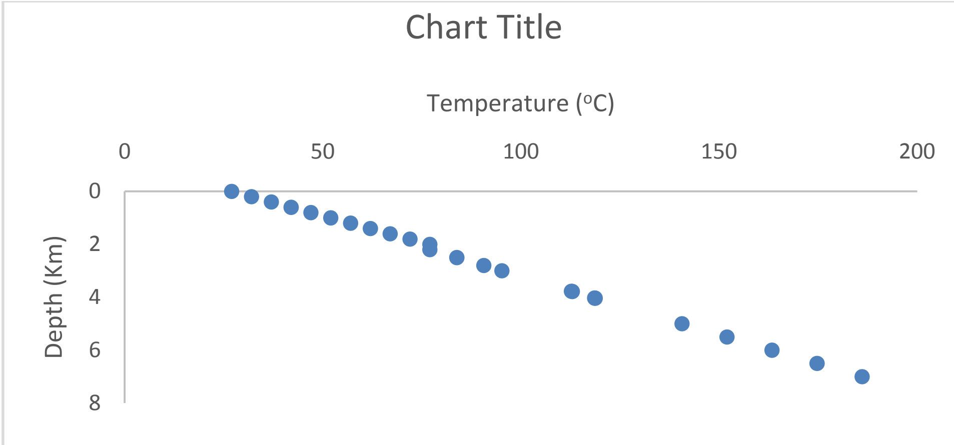


*Fig. 4 :* Computed equilibrium geotherm of the studied area

*Table 1 :* Measured and computed temperatures at some depths for three wells

| Well | Depth (Km) | Measured Temp(oC) | Comp. Temp (Oc) | Difference |
|---|---|---|---|---|
| | 3.218 | 98.89 | 102.323 | -3.43373 |
| | 3.21716 | 98.89 | 102.304 | -3.41406 |
| Well1 | 3.21564 | 98.89 | 102.268 | -3.37849 |
| | 3.80634 | 117.22 | 116.095 | 1.125 |
| | 3.80665 | 117.22 | 116.102 | 1.11774 |
| | 3.80695 | 116.67 | 116.109 | 0.56072 |
| | 3.80875 | 117.22 | 116.151 | 1.06858 |
| well2 | 3.039 | 97.78 | 98.1338 | -0.35387 |
| | 3.051 | 97.78 | 98.4147 | -0.63476 |
| | 3.206 | 107.22 | 102.042 | 5.17715 |
| | 3.3395 | 107.22 | 105.167 | 2.05232 |
| | 3.205 | 107.22 | 102.019 | 5.20056 |
| | 3.38 | 111.11 | 106.115 | 4.99434 |
| | 3.394 | 111.11 | 106.443 | 4.66664 |
| | 3.39 | 111.11 | 106.349 | 4.76027 |
| well3 | 2.9852 | 92.78 | 96.8745 | -4.09458 |
| | 2.981 | 92.78 | 96.7762 | -3.99627 |
| | 2.985 | 92.78 | 96.8699 | -4.0899 |
| | 2.98 | 92.78 | 96.7528 | -3.97286 |
| | 3.041 | 101.67 | 98.1806 | 3.48931 |
| | 3.044 | 101.67 | 98.2509 | 3.41909 |
| | 3.176 | 101.67 | 101.340 | 0.32936 |
| | 3.1766 | 101.67 | 101.354 | 0.31532 |

## V. Conclusion

In this study the analytical solution of the 1-D steady state heat conduction equation based on two layers model was obtained and applied to the study area. Two equations obtained for the two layers were used to generate the temperature structure. The accuracy of the model depends on the accuracy of thermal conductivity, heat production in the sediment and the basal heat flow. Comparison of the computed and measured temperature shows that the difference is minimal and the model is dependable and can be applied for thermal and hydrocarbon modelling in the Niger Delta. Therefore, it is possible to predict subsurface thermal properties without drilling expensive hole and also carrying out temperature logging.

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