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Least-Square Geothermal Models in Crustal Rocks with Non-Radiogenic and Radiogenic Heat Generation Sources in the Niger Delta Basin

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Abstract Geothermal models in crustal rocks with non-radiogenic and radiogenic heat generation sources were developed using temperature data from Continuous Temperature Logs in 26 wells randomly distributed across the Niger Delta Basin. Data analyses and interpretation by the method of Least-squares generated results which show that Ground Surface Temperature (GST) ranged between 5.4 and 53.5°C with a mean of 27.98°C; Geothermal Gradient (Gg) ranged between 0.37 to 3.84°C/100m with a mean of 2.14°C/100m. The mean geothermal distribution functions obtained for both the non-radiogenic and radiogenic heat generation models in the Niger Delta are T=27.983+0.0214y and $T=27.983+0.0214y-2.64x10^{-10}y^2$ respectively. This is very vital in effectively and accurately providing geotemperature information essential in estimating the earth's heat flow; developing the subsidence history including the formation, maturity and migration of hydrocarbon in sedimentary basins, and searching for deep-seated geologic structures favourable to hydrocarbon accumulation.

Keywords Least-square, Geothermal, Non-Radiogenic, Radiogenic, Crustal Rocks and Niger Delta

1. Introduction

The present efforts of exploring deeper prospects towards recovering more untapped hydrocarbon in the Niger Delta Basin require accurate data analyses and in-depth knowledge of geotemperature distribution. Temperature distribution in the earth's subsurface is either of radiogenic source or of formation source or both [1]. Geotemperature distribution in the Continental Crust is governed both by either the conductive heat loss to the surface or heat generated internally by the decay of radioactive isotopes in rocks and heat that flows upward from sub-continental mantle [2].

Several studies have been conducted using the simple gradient method, statistical and geostatistical analyses, thermal resistance method, simple linear increase of temperature with depth among others to determine the geothermal characteristics in different parts of the Niger Delta Basin. A brief review of some of these studies related to geotemperature and its applications and variations are given in Table 1.

This research is focused on generating geothermal models considering the non-radiogenic and radiogenic heat generation sources which contributes a significant amount of heat to the surface heat flow in the Niger Delta Basin and employing the Least-Squares method to fit the best curves, compute sets of geotemperature data using Normal equations to estimate the Ground Surface Temperature, determine the Geothermal Distribution Functions, predict the vertical trend of geothermal gradient and examine the effects of radiogenic heat generation on the thermal parameters in the Niger Delta Basin. This has the advantage of effectively and accurately providing geotemperature information essential in estimating the earth's heat flow; developing sedimentary basins, its subsidence history including the formation, maturity and migration of hydrocarbon; searching for deep-seated geologic structures (faults, anticlines) favourable to hydrocarbon accumulation in oil exploration.

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Table 1. A Review of Studies Related to Geotemperatures

Authors/Studies	Results, Observations, Remarks
[3]	Obtained geothermal gradient between 0.7 and 1.0 °F/100ft in Southern Nigeria sedimentary Basin with the lowest values at the Central portion of the Basin and increased in all directions to about 3 °F/100ft in the Cretaceous rocks in the North
[4]	Obtained geothermal gradient which increases with diminishing sand percentage from 1.84°C/100m in the Continental sands to 2.73°C/100m in the Deltaic section of the Niger Delta
[5]	Computed geothermal gradients based on the simple gradient method in the distal part of the Niger Delta to be between 1.90 and 3.2°C/100m
[6]	Calculated geothermal gradient based on simple gradient method for the Northern Niger Delta and obtained values varying between 1.526 and 2.727°C/100m
[7]	Obtained temperatures of 80–122°C in the Northern and Ughelli Depobelts at a depth of about 2500 m, low temperature of 46–88°C in the Central and Coastal depobelts and moderate temperature of 80–100°C in the offshore depobelts for the same depth of 2500 m; regional geothermal gradient ranged from 1.5–2.5°C/100m in the Coastal Depobelts and offshore regions and increased northwards to 4.5 °C/100m.
[8])	Obtained lowest geothermal gradients of 0.82°C/100m at the Central Niger Delta which increases both northward and seaward up to 2.62°C/100m and 2.85°C/100m respectively in the Continental Sands of Benin Formation; geothermal gradient ranged from 1.83 to 3.0°C/100m in the Central part of the Basin in Agbada Formation and high value of 4.6°C/100m was obtained northwards while intermediate value of 2.5°C/100m was recorded seawards.
[9]	Computed geothermal gradient in North-Western Niger Delta based on a simple linear increase of temperature with depth and obtained gradients varying between 17.12 and 26.67°C/km with average of 21.90°C/km.
[10]	Obtained geothermal gradients which vary from 13.46 to 33.66°C/km with an average of 23.56°C/km for he Eastern Niger Delta.
[11]	Computed the geothermal gradients in the shallow/continental sections in the Niger delta to vary between 10 – 18°C/km onshore, increasing to about 24°C/km seawards, southwards and eastwards. In the deeper (marine/paralic) section, geothermal gradients vary between 18 – 45°C/km.
[12]	Conducted statistical and geostatistical analysis of geothermal data and determined that the spatial variation of geothermal gradient in the study area from the ordinary kriging ranges from 18 to 34.0°C/km, with an average value of 25.5 °C/km.

2. Location and Geology of Niger Delta

The area of study is the Niger Delta sedimentary Basin (Figure 1). It is situated on the Continental margin of the Gulf of Guinea in Equatorial West Africa between Latitudes 3 °N and 6 °N and Longitude 5 °E and 8 °E.

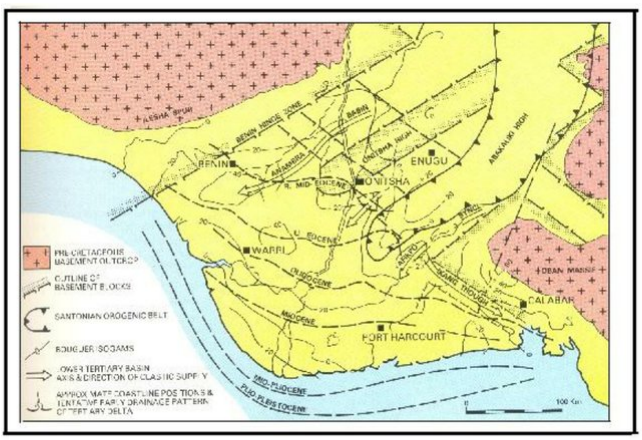

Figure 1. Map of the Niger Delta Sedimentary Basin

Early studies of the Niger Delta Basin [13] subdivided the basin into three formations namely the Akata (base), the Agbada (middle), and the Benin (top) Formations (Figure 2). These Formations represent the prograding depositional facies that are distinguished mostly on the basis of their sand-shale ratios.

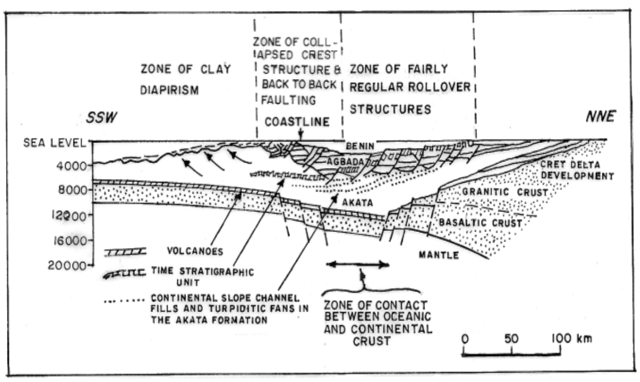

Figure 2. Map showing the stratigraphy of Niger Delta

The Akata Formation comprises mostly marine shale sequences and lowstand turbidite sand. The Agbada Formation comprises alternating sequences of sandstone and shale and is interpreted as a cyclic parallic sequence comprising marine and fluvial deposits. The Benin Formation comprises continental, massive sands with clay intercalations ([4]; [13]; [14]; [15]).

3. Methodology

3.1. Field Data

Geotemperature data from Continuous Temperature Logs in 26 wells randomly distributed across the Niger Delta

Basin were used in this study. These data are reliable since the wells have attained thermal equilibrium after some period of drilling [7].

3.2. Geothermal Model Assumptions

A homogenous earth model [16] is assumed and the dependence of temperature variation on lithology is neglected so as to observe the variations of temperature with depth ([7]; [17]). The earth is modelled as an isotropic slab to the "Moho" depth of about 36 km to allow for analytic solutions to the Normal equations governing heat conduction problems. The earth's crust approximates a plane due to its negligible thickness compared with the thickness of the entire earth. This is a 1-layer problem and 1-dimensional heat flow by conduction is assumed due to the solid nature of the earth's crust.

3.3. Geothermal Model Equations

3.3.1. Non-Radiogenic Heat Generation Case

For a 1-D steady-state heat conduction through an earth crust that approximates a slab without radiogenic heat generation, external heat penetration and shielded from topographic as well as seasonal changes, the diffusion equations is:

$$\frac{\partial^2 T}{\partial y^2} = 0 \quad (1)$$

Given to the great age of the crust, time-dependent effects are generally neglected [2].

Applying the boundary conditions (at y = 0):

(i) $T = T_s$ (Ground Surface Temperature) (2a)

(ii) $q_s = \frac{-kdT}{dy} = -q_s$ (2b)

Then $q_s = -q_s$ because heat is assumed to be flowing out of the earth. Solving equation (1) and applying the boundary conditions, we obtain:

$$T = T_s + \frac{dT}{dy} y \quad (3)$$

Where: $\frac{-kdT}{dy} = -q_s$ and $\frac{q_s}{k} = \frac{dT}{dy}$ (4)

The geotemperature distribution function now becomes:

$$T = T_s + \frac{q_s}{k} y \quad (5)$$

Where: T_s = Ground Surface Temperature (GST) (°C), q_s = Heat flow (W/m^2), k = Thermal Conductivity (W/m°C) and y = Vertical Depth (m).

Equation (5) defines temperature at any depth, y in the earth for a homogenous earth model without radiogenic heat generation. The Least Square equation for this case is given as:

$$T = a_0 + a_1 y \quad (6)$$

With the following Normal equations:

$$\Sigma T = a_0 N + a_1 \Sigma y \quad (7a)$$

$$\Sigma Ty = a_0 \Sigma N + a_1 \Sigma y^2 \quad (7b)$$

Comparing equations (5) and (6), we have: $a_0 = T_s$ and $a_1 = \frac{q_s}{k}$.

3.3.2. Radiogenic Heat Generation Case

If the radiogenic heat (H) is generated per unit volume per unit time, then the heat conduction equation becomes:

$$\frac{\partial^2 T}{\partial y^2} = \frac{-H}{k} \quad (8)$$

Applying the boundary conditions (equations 2a and 2b) and solving equation (8), we obtain:

The geotemperature distribution function:

$$T = T_s + \frac{q_s y}{k} - \frac{Hy^2}{2k} \quad (9)$$

The geotemperature gradient function:

$$\frac{dT}{dy} = \frac{-Hy}{k} + \frac{q_s}{k} \quad (10)$$

Equation (9) defines temperature at any depth, y in an earth model with radiogenic heat generation. The Least Square equation is given as:

$$T = a_0 + a_1 y + a_2 y^2 \quad (11)$$

With the following Normal equations:

$$\Sigma T = a_0 N + a_1 \Sigma y + a_2 \Sigma y^2 \quad (12a)$$

$$\Sigma Ty = a_0 \Sigma y + a_1 \Sigma y^2 + a_2 \Sigma y^2 \quad (12b)$$

$$\Sigma Ty^2 = a_0 \Sigma y^2 + a_1 \Sigma y^3 + a_2 \Sigma y^4 \quad (12c)$$

Comparing equations (9) and (11), we have: $a_0 = T_s$, $a_1 = \frac{q_s}{k}$ and $2a_2 = -\frac{H}{k}$.

Solutions to the Normal equations above are obtained by Matrix equations:

$$B = Ax \quad (13)$$

Where B, A and x are matrices then:

$$x = A^{-1} B \quad (14)$$

Matrix x is that of required solutions a_0, a_1, and a_2 of the sets of Normal equations. Matrices A and B are developed using ΣT, N, Σy, Σy^2, ΣTY, Σy^3, ΣTy^4 in the Normal equations.

Solutions to these equations are obtained by solving the Matrix Algebra using MS Excel package.

4. Results and Discussion

4.1. Ground Surface Temperature (GST)

As stated by [18], the ground surface is an important layer which temperature forms an important boundary condition for the determination of geothermal gradient, a parameter which is useful in evaluating the thermal energy resources of any region. Table 2 shows the ground surface temperature (GST) for the 26 wells in this research.

The GST ranges between 5.369°C for well 7 and 53.350°C for well 6 for both the non-radiogenic and radiogenic models with a mean value of 27.983°C computed for the Niger Delta. This is in agreement with an earlier value of 27°C predicted for the southern Nigeria sedimentary Basin by [3].

4.2. Geothermal Distribution Functions for Non-Radiogenic and Radiogenic Sources

Table 2 also shows the geothermal distribution functions for crustal rocks with non-radiogenic and radiogenic heat generation sources for the 26 wells studied. The Least-Square equations indicate linear functions for the non-radiogenic heat generation model and quadratic functions for the radiogenic heat generation model. The mean geotemperature distribution functions for wells 1-26 are computed respectively as:

For Non-radiogenic Model:

$$T = 27.983+0.02182y \tag{15}$$

For Radiogenic Model:

$$T = 27.983+0.02182y-2.64x10^{-10}y^2 \tag{16}$$

Table 2. Ground Surface Temperatures (GST) and Least-Square Geothermal Distribution Functions for Crustal Rocks with Non-Radiogenic and Radiogenic Heat Generation for the 26 Wells in the Study Area

Well No.	Non-Radiogenic			Radiogenic			
	GST $a_0 = T_s(°C)$	$a_l = \frac{q_s}{k}(°C/m)$	Geothermal Distribution Function $T = a_0 + a_l y$	GST $a_0 = T_s(°C)$	$a_l = \frac{q_s}{k}(°C/m)$	$a_2 = \frac{H}{2k}(°C/m^2)$	Geothermal Distribution Function $T = a_0 + a_l y + a_2 y^2 (°C)$
1	39.380	0.0131	39.38+0.0131y	39.380	0.0131	-9.00E-11	39.38+0.0131y-9E-11y^2
2	12.465	0.0277	12.465+0.0277y	12.465	0.0277	-2.00E-11	12.465+0.0277y-2E-11y^2
3	19.453	0.0175	19.453+0.0175y	19.453	0.0175	-1.00E-11	19.453+0.0175y-1E-11 y^2
4	10.176	0.0299	10.176+0.0299y	10.176	0.0299	-5.00E-10	10.176+0.0299y-5E-10 y^2
5	40.268	0.0139	40.268+0.0139y	40.268	0.0139	-2.00E-11	40.268+0.0139y-2E-11 y^2
6	53.350	0.0134	53.350+0.0134y	53.350	0.0134	-5.00E-12	53.350+0.0134y-5E-12 y^2
7	5.369	0.0311	5.369+0.0311y	5.369	0.0311	-7.00E-13	5.369+0.0311y-7E-13 y^2
8	36.908	0.0153	36.908+0.0153y	36.908	0.0153	-1.00E-10	36.908+0.0153y-1E-10 y^2
9	35.330	0.0182	35.33+0.0182y	35.330	0.0182	-1.00E-19	35.33+0.0182y-1E-19 y^2
10	36.742	0.0155	36.742+0.0155y	36.742	0.0155	-4.00E-11	36.742+0.0155y-4E-11 y^2
11	34.500	0.0128	34.500+0.0128y	34.500	0.0128	-9.00E-11	34.500+0.0128y-9E-11 y^2
12	28.000	0.0209	28.000+0.0209y	28.000	0.0209	-4.00E-12	28.000+0.0209y-4E-12 y^2
13	17.733	0.0325	17.733+0.0325y	17.733	0.0325	-7.00E-13	17.733+0.0325y-7E-13 y^2
14	17.117	0.0377	17.117+0.0377y	17.117	0.0377	-7.00E-10	17.117+0.0377y-7E-10 y^2
15	14.999	0.0357	14.999+0.0357y	14.999	0.0357	-1.00E-11	14.999+0.0357y-1E-11 y^2
16	28.424	0.0152	28.424+0.0152y	28.424	0.0152	-1.00E-10	28.424+0.0152y-1E-10 y^2
17	29.093	0.0329	29.093+0.0329y	29.093	0.0329	-2.00E-11	29.093+0.0329y-2E-11 y^2
18	29.997	0.0384	29.997+0.0384y	29.997	0.0384	-2.00E-09	29.997+0.0384y-2E-09 y^2
19	27.290	0.0150	27.290+0.0150y	27.290	0.0150	-2.00E-12	27.290+0.0150y-2E-12 y^2
20	29.656	0.0156	29.656+0.0156y	29.656	0.0156	-2.00E-10	29.656+0.0156y-2E-10 y^2
21	27.146	0.0150	27.146+0.0150y	27.146	0.0150	-1.00E-11	27.146+0.0150y-1E-11 y^2
22	36.524	0.0210	36.524+0.0210y	36.524	0.0210	-2.00E-10	36.524+0.0210y-2E-10 y^2
23	20.559	0.0281	20.559+0.0281y	20.559	0.0281	-2.00E-09	20.559+0.0281y-2E-09 y^2
24	29.129	0.0370	29.129+0.0370y	29.129	0.0370	-4.00E-10	29.129+0.0370y-4E-10 y^2
25	33.801	0.0037	33.801+0.0037y	33.801	0.0037	-3.00E-10	33.801+0.0037y-3E-10 y^2
26	34.155	0.0103	34.155+0.0103y	34.155	0.0103	-4.00E-11	34.155+0.0103y-4E-11 y^2
Mean	27.983	0.02182	27.983+0.02182y	27.983	0.02182	-2.64E-10	27.983+0.02182y-2.64E-10 y^2

4.3. Geotemperature Gradient of the Niger Delta with Radiogenic Heat Generation

Table 3 shows the geotemperatures and geothermal gradients for depths extrapolated to the "Moho" in the Niger Delta Basin using the mean geotemperature functions (equations 15 and 16) with Non- Radiogenic and Radiogenic heat generations respectively for wells 1-26.

Table 3. Mean Geotemperatures and Geothermal Gradient Functions to the "Moho" in the Niger Delta Basin

Depth, y(m)	Geotemperatures, T (°C)			Geothermal Gradient (Gg) (°C/100m)		
	Non-Radiogenic, T_N	Radiogenic, T_R	$\Delta T = T_N - T_R$	Non-Radiogenic	Radiogenic	$\Delta Gg = Gg_N - Gg_R$
	27.983+0.02182y	$27.983+0.02182y-2.64x10^{-10}y^2$		Gg_N	Gg_R	
0	27.9830	27.9830	0	2.182000	2.182000	0.000000
1000	49.8030	49.8027	0.000264	2.182000	2.181974	0.000026
2000	71.6230	71.6219	0.001056	2.182000	2.181947	0.000053
3000	93.4430	93.4406	0.002376	2.182000	2.181921	0.000079
4000	115.2630	115.2588	0.004224	2.182000	2.181894	0.000106
5000	137.0830	137.0764	0.006600	2.182000	2.181868	0.000132
6000	158.9030	158.8935	0.009504	2.182000	2.181842	0.000158
7000	180.7230	180.7101	0.012936	2.182000	2.181815	0.000185
8000	202.5430	202.5261	0.016896	2.182000	2.181789	0.000211
9000	224.3630	224.3416	0.021384	2.182000	2.181762	0.000238
10000	246.1830	246.1566	0.026400	2.182000	2.181736	0.000264
11000	268.0030	267.9711	0.031944	2.182000	2.181710	0.000290
12000	289.8230	289.7850	0.038016	2.182000	2.181683	0.000317
13000	311.6430	311.5984	0.044616	2.182000	2.181657	0.000343
14000	333.4630	333.4113	0.051744	2.182000	2.181630	0.000370
15000	355.2830	355.2236	0.059400	2.182000	2.181604	0.000396
16000	377.1030	377.0354	0.067584	2.182000	2.181578	0.000422
17000	398.9230	398.8467	0.076296	2.182000	2.181551	0.000449
18000	420.7430	420.6575	0.085536	2.182000	2.181525	0.000475
19000	442.5630	442.4677	0.095304	2.182000	2.181498	0.000502
20000	464.3830	464.2774	0.105600	2.182000	2.181472	0.000528
21000	486.2030	486.0866	0.116424	2.182000	2.181446	0.000554
22000	508.0230	507.8952	0.127776	2.182000	2.181419	0.000581
23000	529.8430	529.7033	0.139656	2.182000	2.181393	0.000607
24000	551.6630	551.5110	0.152064	2.182000	2.181366	0.000634
25000	573.4830	573.3180	0.165000	2.182000	2.181340	0.000660
26000	595.3030	595.1245	0.178464	2.182000	2.181314	0.000686
27000	617.1230	616.9305	0.192456	2.182000	2.181287	0.000713
28000	638.9430	638.7360	0.206976	2.182000	2.181261	0.000739
29000	660.7630	660.5410	0.222024	2.182000	2.181234	0.000766
30000	682.5830	682.3454	0.237600	2.182000	2.181208	0.000792
31000	704.4030	704.1493	0.253704	2.182000	2.181182	0.000818
32000	726.2230	725.9527	0.270336	2.182000	2.181155	0.000845
33000	748.0430	747.7555	0.287496	2.182000	2.181129	0.000871
34000	769.8630	769.5578	0.305184	2.182000	2.181102	0.000898
35000	791.6830	791.3596	0.323400	2.182000	2.181076	0.000924
36000	813.5030	813.1610	0.342144	2.182000	2.181050	0.000950
Mean				2.182000	2.181525	0.000475

The 'Moho' depth (36000 m) mean temperature for wells 1-26 are 813.503°C for the non-radiogenic model and 813.161°C for the radiogenic model. The trend suggests a distributive pattern of geotemperature for the Crust in the Basin. The effect of radiogenic heat generation is pronounced at great depth and negligible at shallow depth. Geothermal gradient is observed to be constant for the non-radiogenic model but decreases with depth for the radiogenic heat model for all the wells studied. The mean geothermal gradient is constant for wells 1-26 at a value of 2.182 (°C/100m) for the non-radiogenic case but decreases with depth from 2.182 to 2.181 (°C/100m) for the radiogenic model.

Figures 3 (a and b) are plots of mean geotemperature (°C) versus depth (m) for wells 1-26 for the non-radiogenic and radiogenic models respectively.

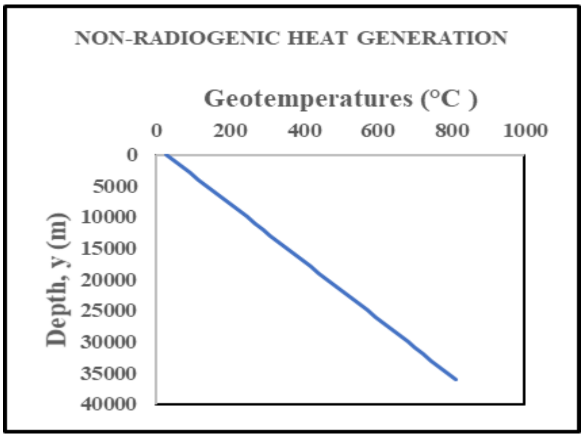

Figure 3a. Geotemperature (°C) versus Depth (m) for the Non-Radiogenic Heat Generation

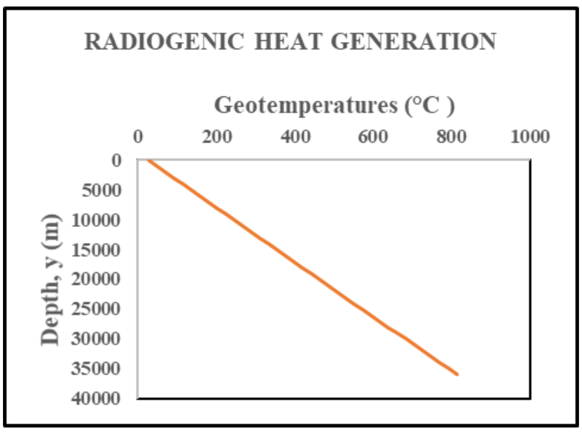

Figure 3b. Geotemperature (°C) versus Depth (m) for the Radiogenic Heat Generation

The curves approximate straight lines due to the insignificant effects of the radiogenic heat sources on the geotemperature gradient. As a result of this, the Moho surface temperatures for both models are similar.

Geotemperature gradient is observed to decrease linearly with depth for the radiogenic heat generation model since the third term of the radiogenic heat generation model equation is infinitesimally small and negligible. This is observed in the linear nature of the graph of radiogenic heat generation model irrespective of the quadratic nature (Figure 4).

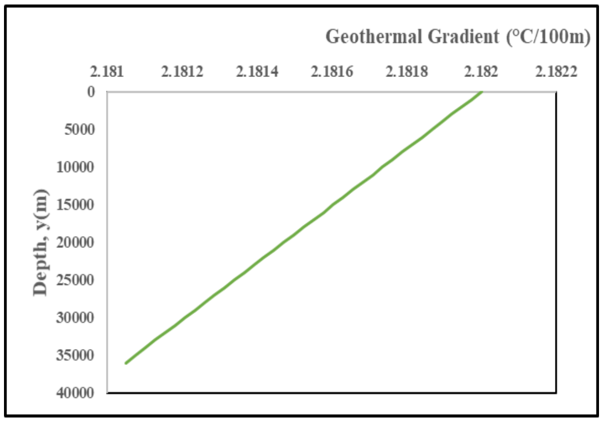

Figure 4. Geothermal Gradient for the Radiogenic Heat Generation

The geotemperature gradient obtained for the non-radiogenic heat generation model is comparable to the results by [4]; [5]; [6]; [8]; [9]; and [12]. The agreement of the results in this study with those of other researchers, irrespective of the different methods used, further supports the low rates of radiogenic heat generation in the Niger Delta Basin obtained in this research.

5. Conclusions

The application of the Least Square method for the computations of ground surface temperature, geothermal gradients and generation of geotemperature distribution functions for the non-radiogenic and radiogenic models is suitable for accurate geotemperature analyses since it gives very close results to those of other researchers using different methods in the Niger Delta.

The radiogenic heat generation source contributes two significant effects on the subsurface temperature distribution in the region. The low value of radiogenic heat generation per unit thermal conductivity accounts for the small difference between the linear and non-linear Least Square geotemperature model values. The radiogenic model also shows that geotemperature gradient decreases infinitesimally with depth. This can be because of the concentration of radiogenic heat sources with depth based on the stratigraphy in the Niger Delta [13]. The increase in shaliness in the Basin can be viewed as decreasing with depth. This is substantiated by the general trend of decrease in radiogenic heat sources from Crust to the Mantle [1].

It is obvious from the foregoing that the geothermal models of the Niger Delta crust is not significantly affected by the radiogenic heat production of the region.

6. Recommendations

The geothermal models developed for the Niger Delta Basin crustal rocks considering radiogenic heat generation and employing the Least Squares method provide new frontiers for research in hydrocarbon and geothermal energy resources appraisal in the Basin. A detailed experimental work using Temperature Logs, Gamma Ray Logs (to obtain radiogenic heat generation) and core samples (to determine thermal conductivity) should be conducted in the study area to obtain results for comparison with the approach in this study.

Further research should be devoted to the study of the effects of other thermodynamic conditions apart from radiogenic heat generation on geotemperature distribution in the Niger Delta and other sedimentary Basins.

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