

SPATIAL VARIATION MODELING OF GEOTHERMAL GRADIENT AND HEAT FLOW IN EASTERN PARTS OF NIGER DELTA SEDIMENTARY BASIN, NIGERIA.

ABSTRACT:

The aims of this research are to carry out statistical and geostatistical analysis of geothermal data and to determine the spatial variation of geothermal gradient and heat flow of parts of Niger delta sedimentary basin. Corrected Bottom hole temperatures from 18 deep oil wells were used for the computation of geothermal gradient and heat flows. The data were compiled from previous work. Both statistical and geostatistical analysis involving histogram, variogram, and ordinary kriging were applied to the data. The computed geothermal gradient values range from 16 – 33°C/Km while the heat flow ranges from 23 to 70mW/m². The statistical analysis of the geothermal data is shown in the table below

Parameter	minimum	maximum	median	mean	Standard deviation	Variance
Geothermal Gradient (°C/Km)	15.57	33.66	21.27	22.51	5.07	25.705
heat flow mW/m ²	21.99	70.31	44.19	45.44	13.92	193.77

Table: 1

The most occurrence geothermal gradient interval in the histogram is 20-24 with a frequency of 9. The experimental variograms for the geothermal gradient and heat flow were modeled with gaussian functions respectively. Both variograms have nugget effect. The values of variances are assumed to be the values of the sill of the geothermal gradient and heat flow in the study area. The omnidirectional variogram provides a good interpretation for the spatial relationships for the two data sets. The ordinary kriging maps obtained from the variogram models for the geothermal gradients and heat flows provided a very good estimate for the un-sampled points. The geothermal gradient kriging map shows that the southwest region is associated with high value. The northwest and central parts have low geothermal gradient respectively. The kriging map of the heat flow shows that highest heat flow occurs in the eastern and parts of the southwest region. The lowest heat flow which trend in the north – south directions is found in the central region of the study area.

Keyword: Geothermal gradient; Heat flow; statistics; variogram; kriging.

I. INTRODUCTION

The Niger Delta is one of the major sedimentary basins and the only discovered hydrocarbon bearing (for now) in Nigeria. It is ranked among the world major hydrocarbon reserve and it has been known for its large accumulation of oil and gas [1, 2]. As a result of the abundance of oil and gas in the region, exploration and exploitation works started fifty years ago.

Many geoscientists [3, 4, 5] have computed the geothermal gradients and heat flow of the Niger Delta. According to [5], the heat flow of the northern Niger Delta sedimentary basin varies between 38.70 mWm^{-2} and 64.28 mWm^{-2} with an average of 51.49 mWm^{-2} . The geothermal gradients of the Niger delta computed from well log by [6] ranges from 0.7 to $1.0^\circ\text{F}/100 \text{ ft}$ at the centre and $3^\circ\text{F}/100\text{ft}$ in the northern part. [4], computed the geothermal gradient and heat flow in parts of the eastern Niger delta from 71 wells and obtained geothermal gradient varying between 12 to $24^\circ\text{C}/\text{Km}$ with an average of $17.6^\circ\text{C}/\text{Km}$ in the coastal swamp, $14^\circ\text{C}/\text{Km}$ to $26^\circ\text{C}/\text{Km}$ with an average of $20.4^\circ\text{C}/\text{Km}$ in the shallow offshore. They also observed heat flow values ranging from 29 to 55 mWm^{-2} with a mean of 42.5 mWm^{-2} .

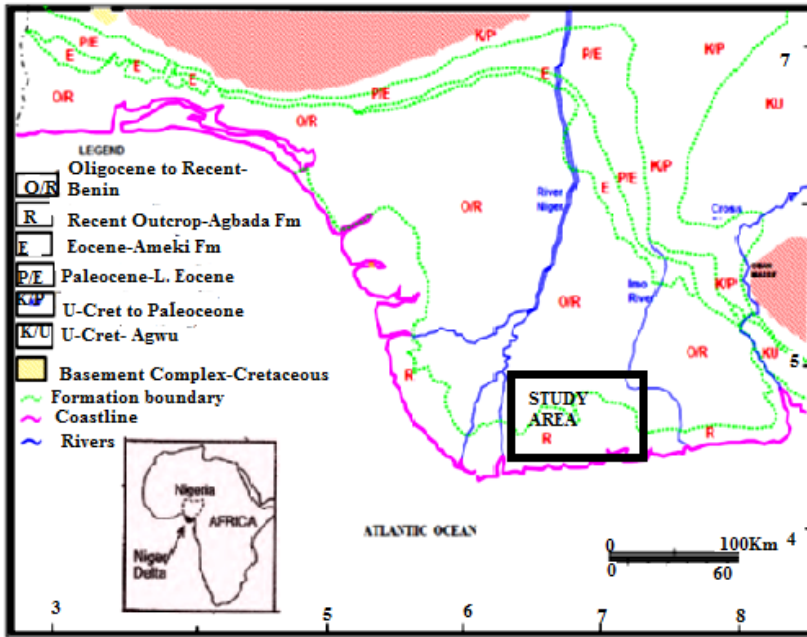
Geothermal gradient and heat flow spatially vary from place to place. Geostatistics make use of statistical tools for incorporating the spatial locations of observations in data processing, allowing for description and modelling of spatial patterns and estimation at unsampled locations [7, 8]. The geothermal gradients and heat flow values in the distal part of the Niger delta varies between 19 - $32^\circ\text{C}/\text{Km}$ and 45 - 85 mWm^{-2} respectively according to [9]. Geothermal gradients values ranging from 25.47 to $31.16^\circ\text{C}/\text{Km}$ with an average of $28.64^\circ\text{C}/\text{Km}$ and heat flow values ranging from 38.93 to 89.59 mWm^{-2} were also obtained in parts of Delta state, Nigeria [10]. The accurate prediction of subsurface geothermal data spatial distribution is very important in sedimentary basin modelling, crustal tectonics and hydrodynamics analysis, hydrocarbon and geothermal exploration. One technique that can be used to assess the spatial variation of geothermal data is geostatistics. This research focus on the modeling of the spatial variation of geothermal gradient and heat flow in the study area.

The objectives of the work are to determine the values of the heat flow and geothermal gradient in areas where there are no bottom hole temperature and to obtain a general view of the spatial variation of the geothermal data within the study area. The variogram model of the data was used for the Kriging estimation techniques.

Geostatistical methods analyse random events in terms of their spatial characteristics. They provide tools for explaining spatial continuity and the possibilities of regression models by incorporating spatial continuity in the model [11]. These methods are used to interpret and predict the spatial distribution of the analyzed phenomena [11, 12]. The geostatistic prediction involves the modeling of the experimental variogram and the estimation of heat flow and geothermal gradient at un-sampled locations. The modeled variogram was used for the analysis of the continuity, homogeneity and spatial structure of the data. The geostatistical estimation using ordinary kriging technique depends on the properties of the modeled variogram.

2. SUMMARY OF THE GEOLOGY OF THE STUDY AREA

79 The study area is located within the eastern parts of the Niger Delta sedimentary basin. It is
80 located within Longitude 5.5 to 8°E and latitude 3.5 to 6.5°N (Fig. 1).The geology of the
81 Niger Delta and its hydrocarbon distribution pattern have been discussed by many researchers
82 [13, 14]. The Niger Delta is one of the most prolific areas in the world [15]



83
84 Fig. 1: Map of Niger Delta Showing the Study Area(Modified from [16].)

85
86 Three lithostratigraphy are present in the Niger Delta. The lithostratigraphy are Benin,
87 Agbada and Akata Formations (Fig. 2). Hydrocarbon accumulation in the Niger Delta is
88 confined to the AgbadaFormation[17].The uppermost section is the continental deltaic plain
89 sands which is known as the Benin Formation. The Benin Formation is underlies by the
90 Agbada Formation which is made up of alternation of sand and shale. The basal Akata
91 Formation is made up of marine prodelta shale. Majority of the hydrocarbon accumulations in
92 the Niger Delta occur in the Agbada Formation.

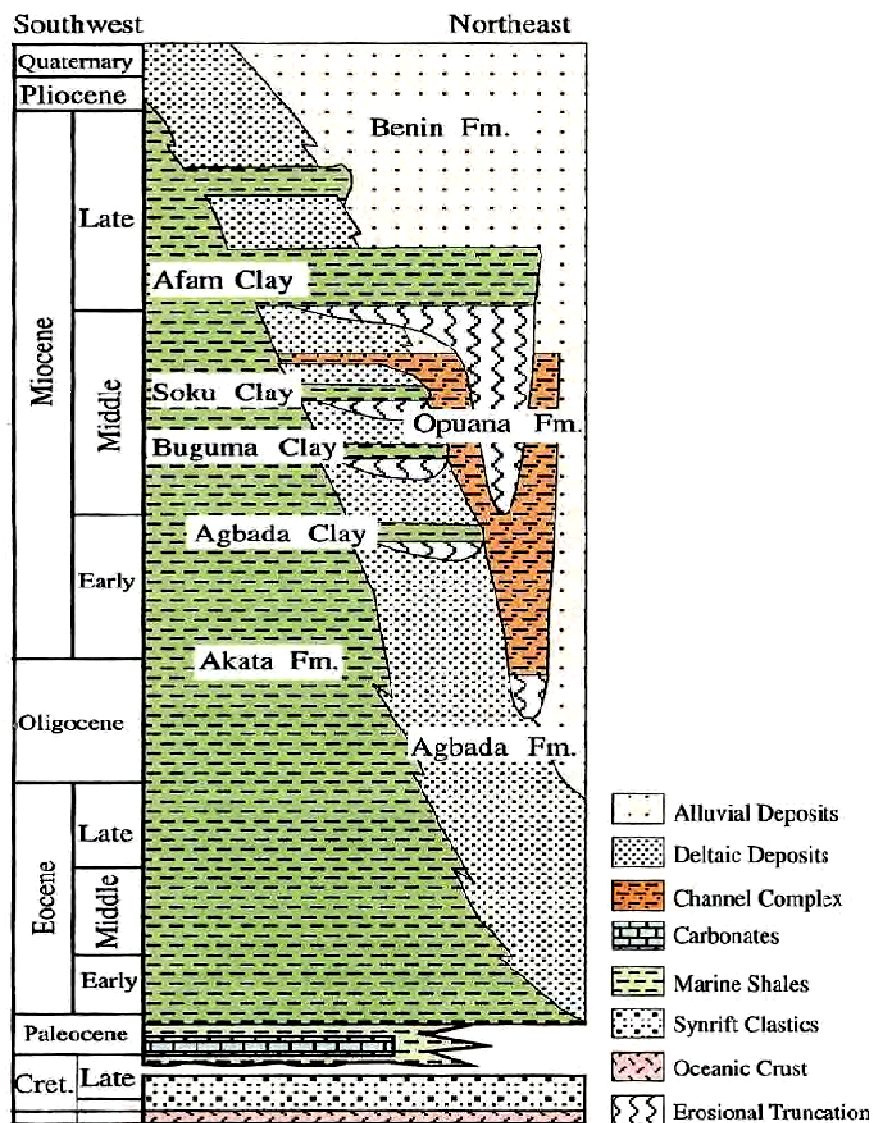


Fig. 2: Lithostratigraphy of the Niger Delta

The Niger Delta is the youngest basin within the Benue Trough system. Its development began after the Eocene tectonic phase and it has an average sedimentary thickness of about 12km. The Rivers Niger and Benue are the major source of sediments to the basin. Growth structures are common in the Niger Delta and they aid in the structural trap of the hydrocarbon [18, 19, 1]

3.METHODOLOGY

3.1 DATASET

The basic data used for this work are geothermal gradient and heat flow data obtained from previous study [20]. The geothermal gradient and heat flow were computed from corrected bottom hole temperatures and suite of well log obtained from 19 exploratory wells. The well logs data and bottom-hole temperature were obtained from Shell Petroleum Development Company. The average geothermal gradient and heat flow of each well was checked for quality and outliers. The procedure adopted includes; Exploratory data analysis, Variogram fitting and Kriging.

3.2 EXPLORATORY DATA ANALYSIS

Exploratory Data Analysis is usually applied to data prior to geostatistical analysis. The purpose of the statistical analysis is to inspect the data properties whether there is a pattern in the dataset. The histogram of the data were plotted and after that the summary statistics was computed. The computed statistics include the minimum, maximum, mean, variance and standard deviation of the data [\(Show the results, the data in a table\)](#). Finally, the histogram was plotted in the x-axis while the frequency (number of values per bin) in the Y-axis.

3.3 VARIOGRAM ANALYSIS

A variogram might be thought of as "*dissimilarity* between point values as a function of distance", such that the dissimilarity is greater for points that are farther apart than points that are closer. The variogram is used for describing the structure of variations in a localised or regionalized variable [21, 22]. It explains the variance in variable values due to differences in spatial locations of the analysed parameters. The semi-variogram is a function that provide half the variance of the continuity between all points separated by distance (h) and is inversely proportional to the distance of points in spatial analysis. The semi-variogram which is half the variogram is commonly used for modeling spatial distribution of data. The semi-variogram can be obtained with the equation [22, 11]:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i + h) - Z(x_i)]^2 \quad (1)$$

Where:

$Z(x_i)$ = value of data

X_i = locations where measurement were performed

$N(h)$ = number of pairs of points ($x_i, x_i + h$) separated by distance h

The experimental variogram is not enough for data analysis. Therefore appropriate theoretical models are fitted on the generated variogram. Several theoretical models such as gaussian,

spherical, linear and exponential [21], were fitted on the experimental variogram and the best fit was selected.

3.4 KRIGING ANALYSIS

Kriging techniques provides the best linear unbiased estimators of the value of the analyzed regionalized variable. It is a geostatistical method that supports the identification of regularities in spatial distribution of data, and those regularities are used in spatial interpolation [11]. The kriging methods are used to estimate the unknown values of the analyzed phenomenon in a given location based on measurements (observations) performed at several known coordinates points. The kriging interpolation was calculated as a linear combination of regionalized random variables as shown in the equation 2:

$$Z^*(s_0) = \sum_{i=1}^n w_i Z(s_i) \quad (2)$$

where:

$Z^*(s_0)$ = estimated value,

$Z(s_i)$ = values observed in known locations,

W_i = weights or importance of the value $Z(s_i)$. It account for the distance between data and data estimation locations, their spatial configuration and spatial structure described by a theoretical semi-variogram.

4. RESULTS

The spatial distribution of geothermal gradient and heat flow computed from available bottom-hole temperatures are shown in Figs. 3 and 4

(your data have absolutely the same distribution. Is it Normal? You need to double check first your 2 sets of Data; the graphs (points) have exactly the same distribution? If yes please write the relationship between the geothermal gradient and heat flow... (it should be Linear...) If what you said is correct....

Before doing anything else you have to double check your data... please plot (geothermal gradient Vs Heat Flow) to confirm

Something is wrong in your data... If Fig 3 and Fig 4 look the same... then their corresponding histogram Fig 5 and Fig 6 should be the same....

The histograms generated for the geothermal gradient and heat flow are shown in Figs 5 and 6. The summary of the statistical analysis of the two datasets is shown in Table 1.

Figs. 7 and 8 show the computed experimental semi-variograms of the geothermal gradient and heat flow of the area. In both cases, the semi-variogram values increase with the separation distance, reflecting that the geothermal gradient and heat flow values close to each

other are more alike, and thus their squared difference is smaller than those far apart. The modeled variograms were used for generating the ordinary kriging maps of the geothermal gradient and heat flow (Figs 9 and 10) respectively. The geothermal gradient and heat flow variogram were modeled with gaussian function and the two variograms also have nugget effect. [\(Which tools or software do you use to do your modeling? you need to add a reference here...\)](#)

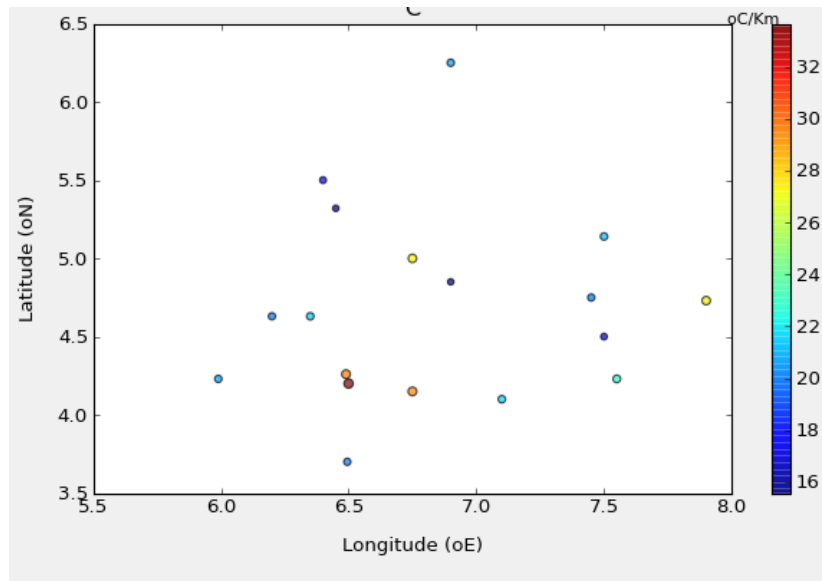
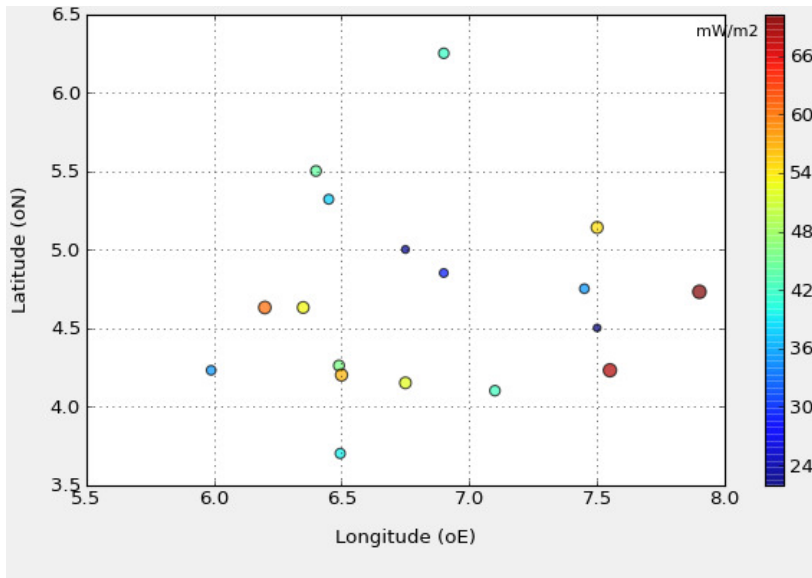
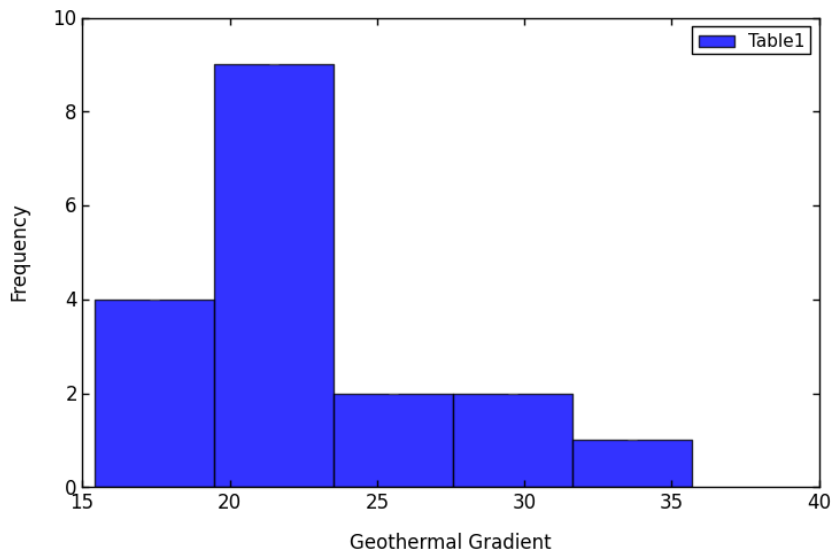


Fig.3: Base Map of the Study Area Showing the Geothermal Gradient Values (°C/Km)



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182 Fig.4: Base Map of the Study Area Showing the Heat Flow Values (mW/m^2)



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184 Fig.5: Histogram of the Geothermal Gradient ($^{\circ}\text{C/Km}$)

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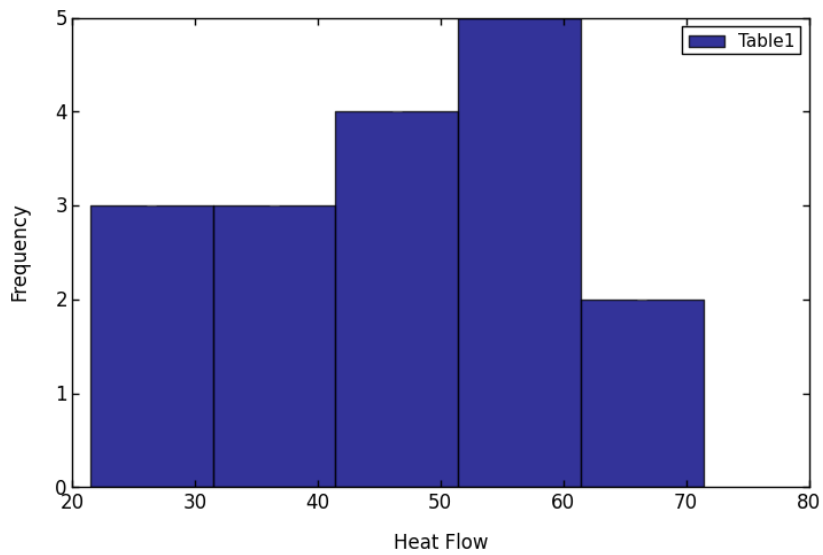


Fig.6: Histogram of the Heat Flow (mW/m²)

Table 1: Summary of Computed Geothermal Gradient and Heat Flow Statistics

Variable	Minimum	Maximum	Median	Mean	Standard deviation
Geothermal gradient (°C/Km)	15.57	33.66	21.27	22.51	5.07
Heat Flow (mW/m ²)	21.99	70.31	44.19	45.44	13.92

[Table \(2\)](#)

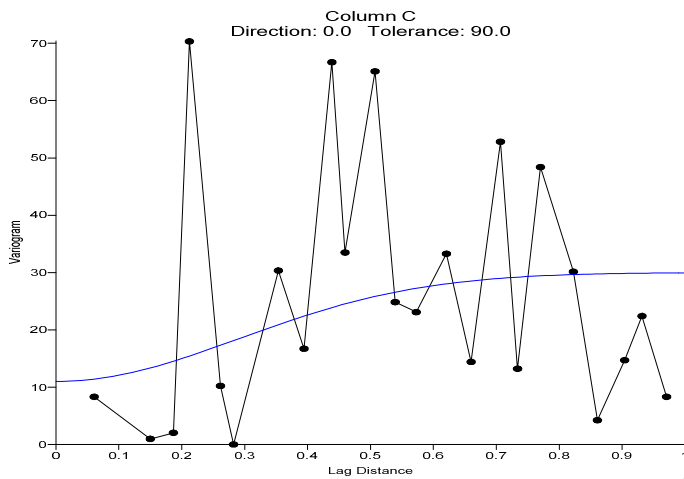


Fig.7: Computed variogram and variogram model for geothermal gradient.

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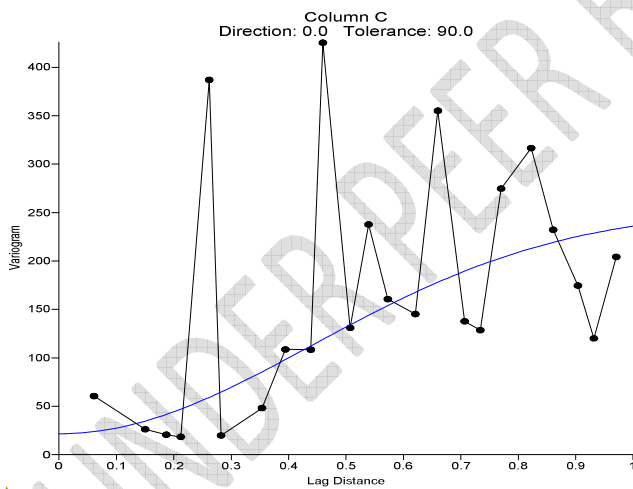


Fig.8. Computed variogram and variogram model for heat flow

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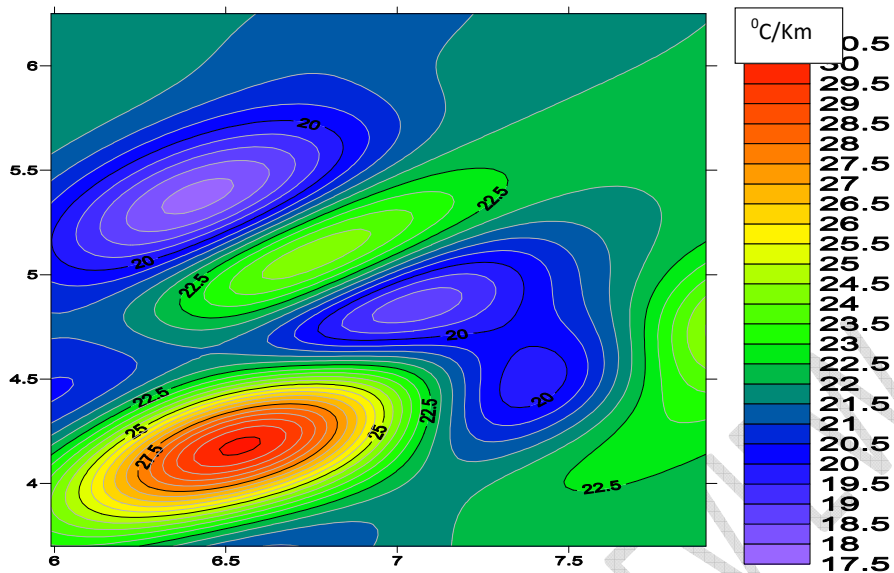


Fig.9. Geothermal gradient map calculated using ordinary kriging algorithm

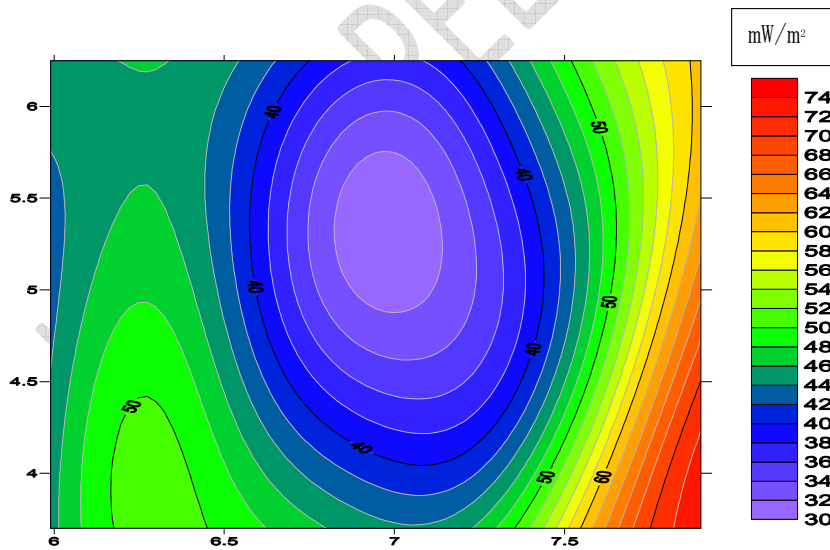


Fig.10: Heat flow map calculated using ordinary kriging algorithm.

The results of the statistical analysis of the geothermal gradient show that the minimum, maximum, median, mean and standard deviation are: 15.57, 33.66, 21.27, 22.51 and 5.07. The most occurrence geothermal gradient interval is 20-24 with a frequency of 9. For the heat flow values, the minimum, maximum, median, mean and standard deviation are: 21.99, 70.31, 44.19, 45.44, and 13.92. The results also show that the median and the mean are almost the same values. This is an indication that the data are normally distributed. The most occurring heat flow interval is 51-61 with a frequency of 5.

With reference to Figs 7 and 8, a Gaussian model was fitted to the two variograms respectively. The variogram models have nugget effects because they did not start from the origin. The variance of the geothermal gradient and heat flow are 25.705 and 193.77 respectively. These values of variances are assumed to be the values of the sill of the geothermal gradient and heat flow in the study area.

5. DISCUSSION

The estimated geothermal gradient in the study area from the ordinary kriging ranges from 18 to 30.5°C/km, with an average value of 25.5 °C/km. The distribution of the geothermal gradient shows that the southwest region is associated with high value. The northwest and central parts have low geothermal gradient respectively. The estimated heat flow from the ordinary kriging analysis in the study area ranges from 24 to 74 mW/m², with an average of 47.0 mW/m². The highest heat flow occurs in the eastern and parts of the southwest region. The lowest heat flow which trend in the north – south directions is found in the central region of the study area. The low heat flow may be attributed to high sedimentary thickness [23]. Generally, the heat flow increases toward the eastern region.

It can be inferred from the study that the factors influencing the thermal regime include tectonic evolution, depth to basement, sedimentary thickness and hydrothermal convection. The study area is tectonically not active and minute heat is supplied from the mantle into the basin. The estimated geothermal gradient and heat flow are in agreement with the values obtained in other tectonically stable and inactive regions of the world [24, 25].

Other possible factors affecting the thermal regime of the area are hydrothermal convection of fluids through local and regional faults and fractures, and hydrocarbon fields. Seismic data obtained from the Niger Delta [26, 18, 19] showed the presence of growth faults in the subsurface. These faults are partly responsible for direction of migration of subsurface fluid. The central region of the heat flow map with low heat flow may be as a result of high sedimentary thickness and depth to basement while the eastern region with high heat flow may be attributed to low sedimentary thickness and depth to basement.

5. CONCLUSION

The statistical and geostatistical analysis techniques have been used for performing spatial distribution and estimation of the geothermal gradient and heat flow at un-sampled points. Spatial dependency of the parameters were moderate. Gaussian model with nugget effects were used for the spatial variation of the geothermal gradient and heat flow variograms. ([You need to show the result of your choice... Show the data why you choose gaussian model... we want to see...](#)) The ordinary kriging maps obtained from the variogram

models shows a very good estimate of the missing data at the unsampled points. The geostatistics modelling show spatial distribution models and spatial dependence levels of the geothermal data. Gaussian model was fitted to the computed variograms. The assessment of the spatial variability of the geothermal gradient and heat flow is very important in basin modelling

COMPETING INTERESTS

The authors hereby declared that there are no competing interests.

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