

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

Abstract:

Aim: The aims of this research are to carry out statistical and geostatistical analysis of geothermal data in the study area and to determine the spatial variation of geothermal gradient and heat flow of parts of Niger delta sedimentary basin.

Methodology: 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, variogram modelling and ordinary kriging were applied to the data.

Results: The computed geothermal gradient values range from 16 – 33 °C/Km while the heat flow ranges from 23 to 70 mW/m². The statistical analysis of the geothermal gradient shows that the minimum, maximum, median, mean and standard deviation are; 15.57, 33.66, 21.27, 22.51 and 5.07 respectively. The results showed that the median and the mean are almost the same values. The most occurrence geothermal gradient interval in the histogram 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. The most occurring heat flow interval is 51-61 with a frequency of 5. The experimental variograms for the geothermal gradient and heat flow were modeled with linear functions respectively. . The variance of the geothermal gradient and heat flow are 25.705 and 193.77 respectively. These value 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 interpretations 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 estimates for the un-sampled points. The geothermal gradient kriging map shows low value in the northern regions and high values in the southern region. The kriging map of the heat flow shows a low values in the central region and high values in the norther and southwest regions respectively.

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

1. 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 reserved and it has been known for its large accumulation of oil and gas. As a result of the abundance of oil and gas in the region, exploration and exploitation works have been on for about fifty years now. Several studies on the geothermal regimes of different parts of the basin have been carried out.

Many geoscientists have computed the geothermal gradients and heat flow of the Niger Delta. According to [1], 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 [2] 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. [3], 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}

. 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 [4]. Anomohanran⁵ obtained 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} in parts of Delta state, Nigeria.

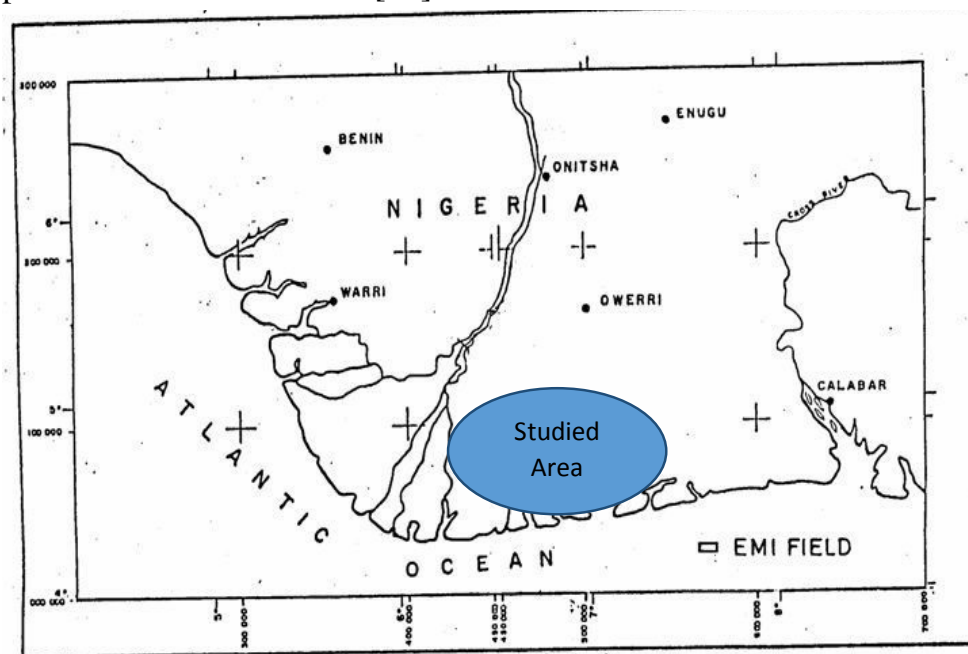
Geothermal gradient and heat flow spatially vary from place to place. Geostatistics make use of statistical tools for incorporating the spatial locations of observations in data processing, allowing for description and modelling of spatial patterns and estimation at unsampled locations [6, 7]. The accurate prediction of subsurface geothermal data spatial distribution is very important. Therefore, there is need to model the spatial variation of the geothermal data in order to be sure of the accuracy of the data when using them for sedimentary basin modelling, analysis of crustal tectonics and hydrodynamics, hydrocarbon maturity, generation and migration and for hydrothermal resource investigation. One techniques that can be used to assess the spatial variation of geothermal data is geostatistics. This research is concerned with the modelling of the spatial variation of geothermal gradient and heat flow in the study area. The model variogram of the data was used for the Kriging estimation techniques.

Geostatistical methods analyze 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. These methods is used to interpret and predict the spatial distribution of the analyzed phenomena [8, 9]. The geostatistic prediction involved the modelling of the experimental variogram and data estimation un-sampled points. The modelled 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 modelled variogram.

2. Summary of the Geology of the Study Area.

The study area is located within the eastern parts of the Niger Delta sedimentary basin. It is located within Longitude 5.5 to 8°E and latitude 3.5 to 6.5°N (Fig. 1). The geology of the Niger Delta and its hydrocarbon distribution pattern have

80 been discussed by many researchers [10, 11]. The Niger Delta is one of the most
81 prolific areas in the world [12].



82
83 Fig. 1: Map of Niger Delta Showing the Study Area

84
85 Three lithostratigraphy are present in the Niger Delta. The lithostratigraphy are
86 Benin, Agbada and Akata Formations. Hydrocarbon accumulation in the Niger
87 Delta is confined to the Agbada formation [13]. The uppermost section is the
88 continental deltaic plain sands which is known as the Benin Formation. The
89 Benin Formation is underlies by the Agbada Formation is made up of
90 alternation of sand and shale. The basal Akata Formation is made up of marine
91 prodelta shale. Majority of the hydrocarbon accumulations in the Niger Delta
92 occur in the Agbada Formation.

93
94 The Niger Delta is the youngest basin within the Benue Trough system. Its
95 development began after the Eocene tectonic phase and it has an average
96 sedimentary thickness of about 12km. The Rivers Niger and Benue are the
97 major source of sediments to the basin. Growth structures are common in the
98 Niger Delta and they aid in the structural trap of the hydrocarbon.

99 100 3. METHODOLOGY

101 The basic data used for this work are geothermal gradient and heat flow data obtained from
102 previous study [14]. The geothermal gradient and heat flow were computed from bottom

hole temperatures and suite of well logs 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. Those data that are below and above certain values were removed from the data set. It was assumed that these outliers are due to errors and do not represent the real geothermal condition of the area. The procedure adopted includes; Exploratory data analysis, Variogram fitting and Kriging.

3.1 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 patterns 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. Finally, the histogram was plotted in the x-axis while the frequency (number of values per bin) in the Y-axis.

3.2 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. It explain the variance in variable values due to differences in spatial locations of the analysed parameter. The semi-variogram is a function that provides half the variance of the continuity between all points separated by 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 obtain with the equation [15, 8]:

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

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 good enough for data analysis. Therefore appropriate theoretical models are fitted on the generated variogram. Several theoretical models such as gaussian, spherical, linear and exponential [16], were fitted on the experimental variogram and the best fit was selected.

3.3 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. The kriging methods are applied to estimate the value of the analyzed phenomenon in a given location based on measurements (observations) performed at several points with known coordinates. The kriging interpolation was calculated as a linear combination of regionalized random variables as:

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

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.

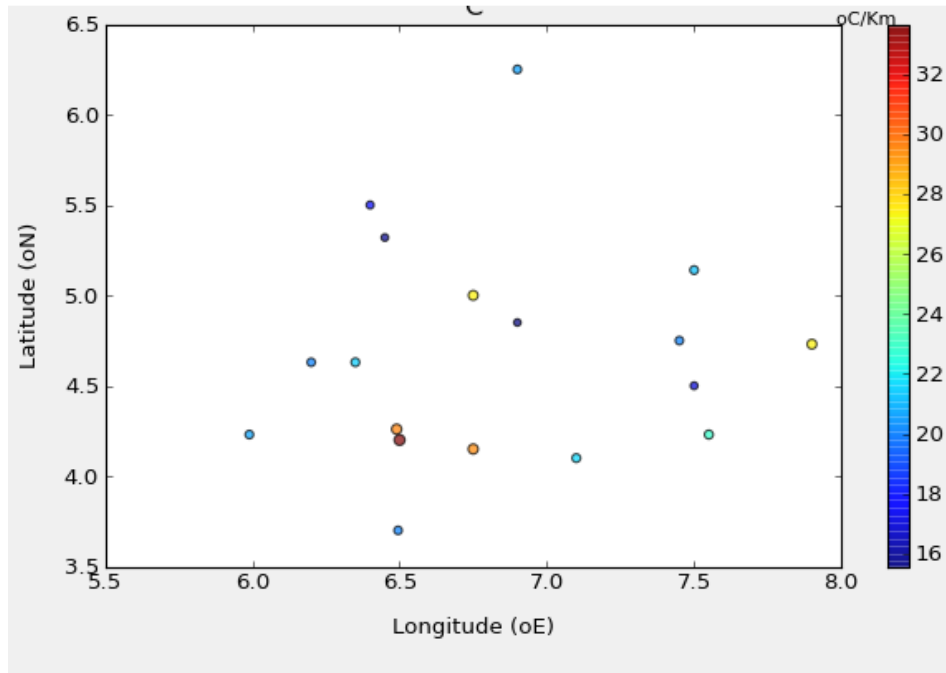
4. RESULTS AND DISCUSSION

The spatial distribution of geothermal gradient and heat flow computed from available bottom-hole temperatures are shown in Figs. 2 and 3. These geothermal data were used for geostatistical the study. The geothermal gradient and heat flow data were checked for outliers such that the data below and above certain range were removed from the datasets before the geostatistical analysis was applied. These extreme values probably are the result of measurement or notation errors and do not represent the real thermal conditions. A total of 18 datasets were used for the geothermal gradient and heat flow spatial analysis respectively.

The histograms generated for the geothermal gradient and heat flow are shown in Figs 4 and 5. The summary of the statistical analysis of the two datasets is shown in Table 1. These statistics were used to evaluate a model and find its optimal parameters for the semivariogram.

Figs. 6 and 7 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 model variograms were used for generating the ordinary kriging maps of the geothermal gradient and heat flow (Figs 8 and 9) respectively.

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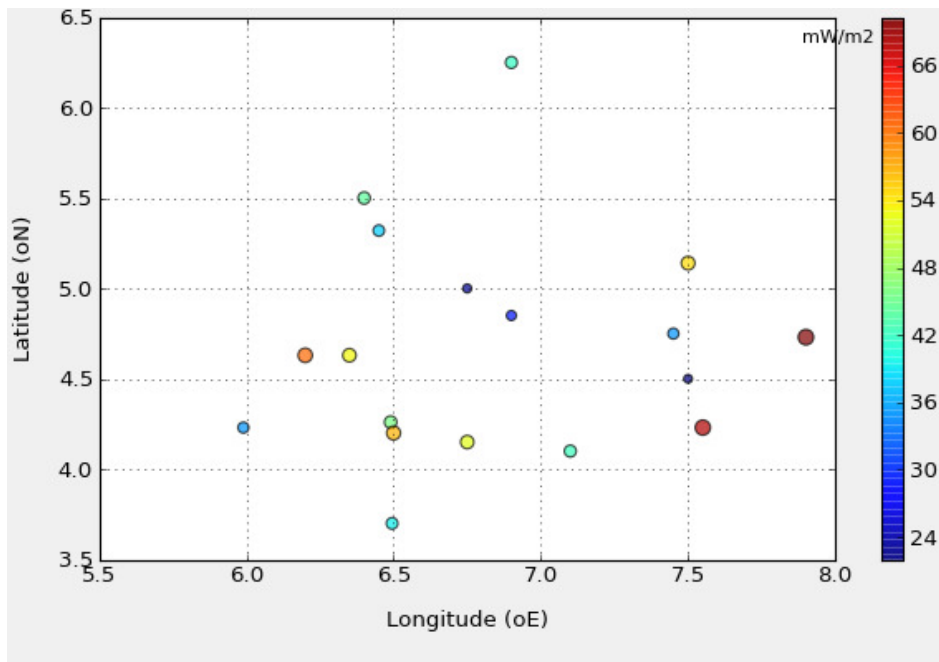


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Fig. 2: Base Map of the Study Area Showing the Geothermal Gradient Values ($^{\circ}\text{C}/\text{Km}$)

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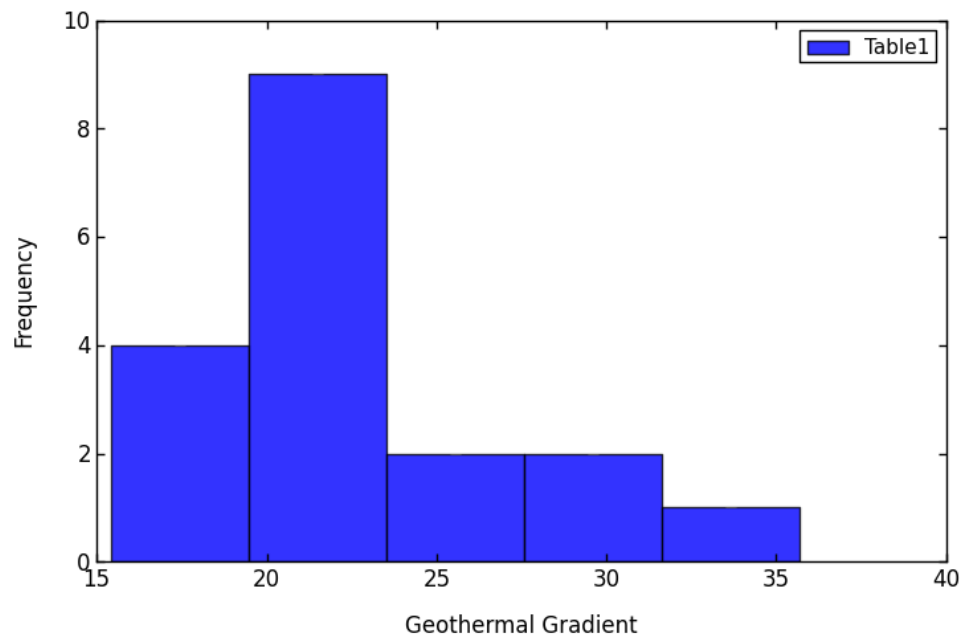


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Fig. 3: Base Map of the Study Area Showing the Heat Flow Values (mW/m^2)

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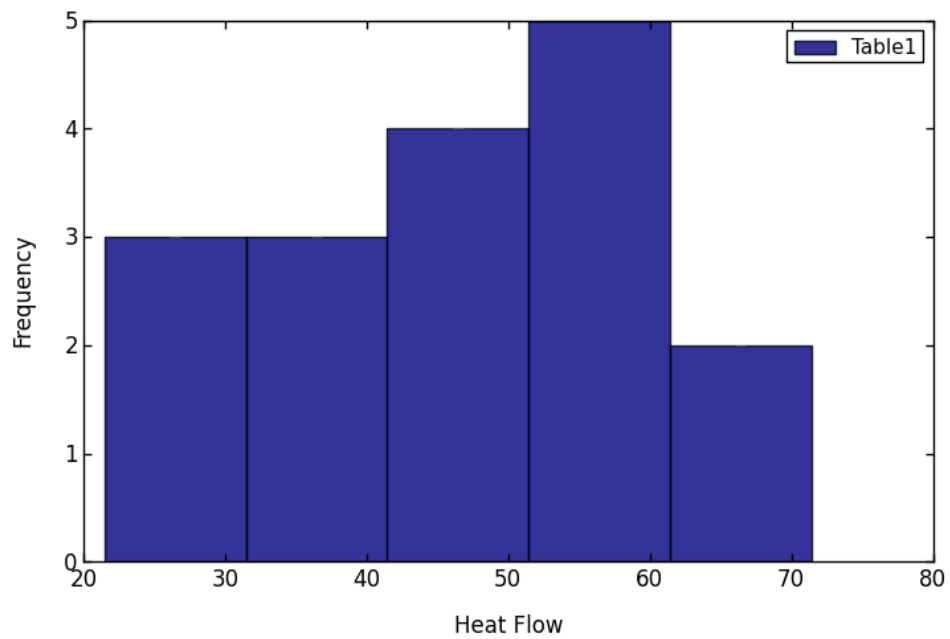


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Fig. 4: Histogram of the Geothermal Gradient

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Fig. 5: Histogram of the Heat Flow

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

Variable	Minimum	Maximum	Median	Mean	Standard deviation
Geothermal gradient	15.57	33.66	21.27	22.51	5.07
Heat Flow	21.99	70.31	44.19	45.44	13.92

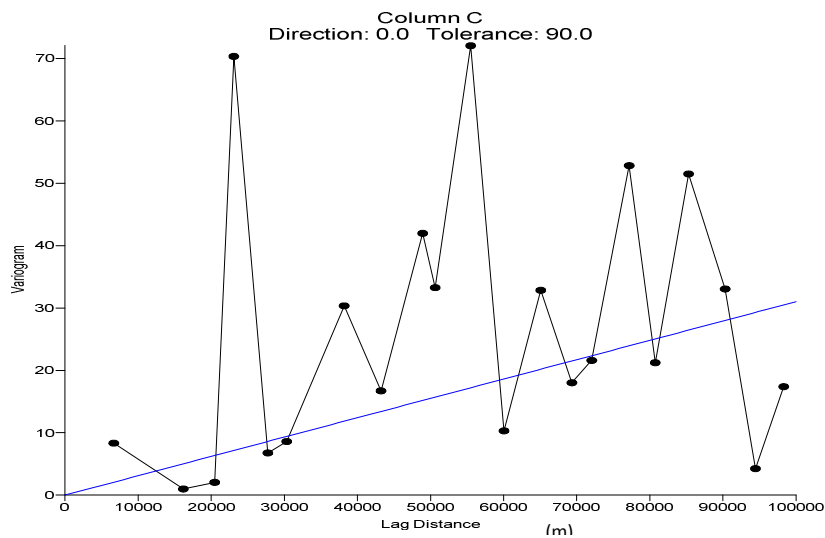
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191 **Fig. 6:** Computed variogram and variogram model for geothermal gradient.

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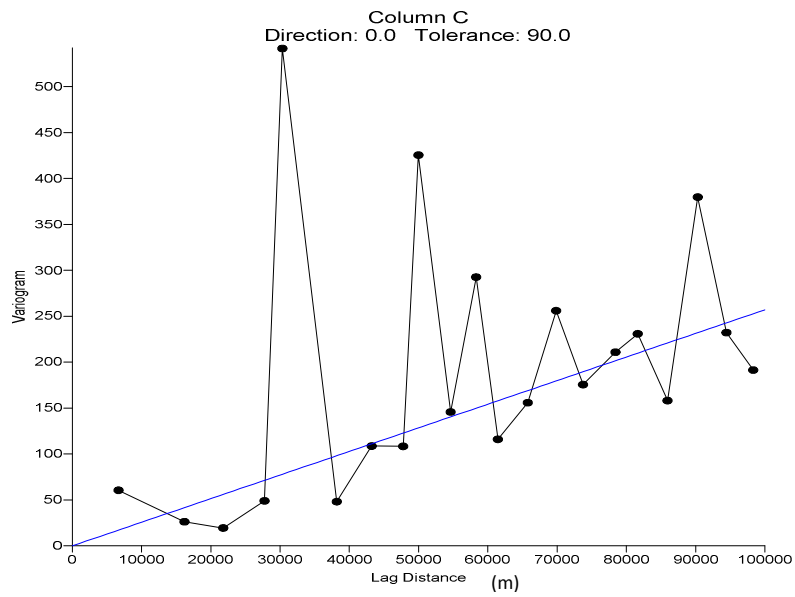


Fig. 7. Computed variogram and variogram model for heat flow

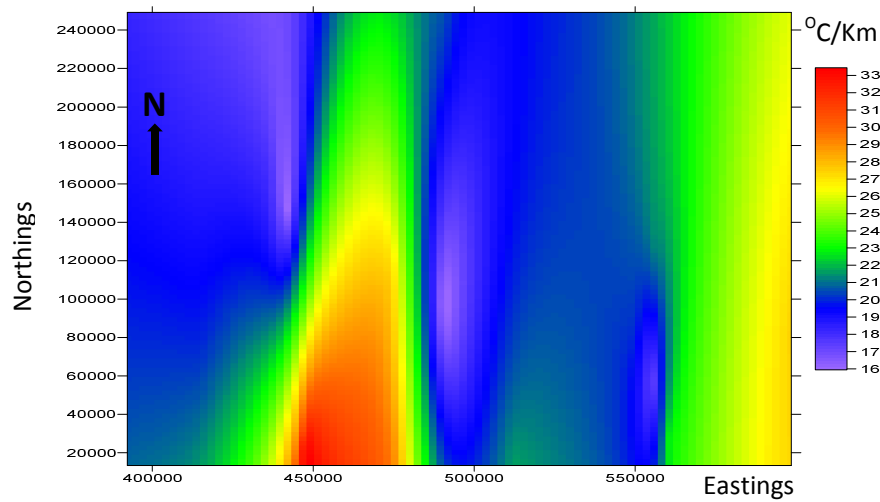


Fig. 8. Geothermal gradient map calculated using ordinary kriging algorithm

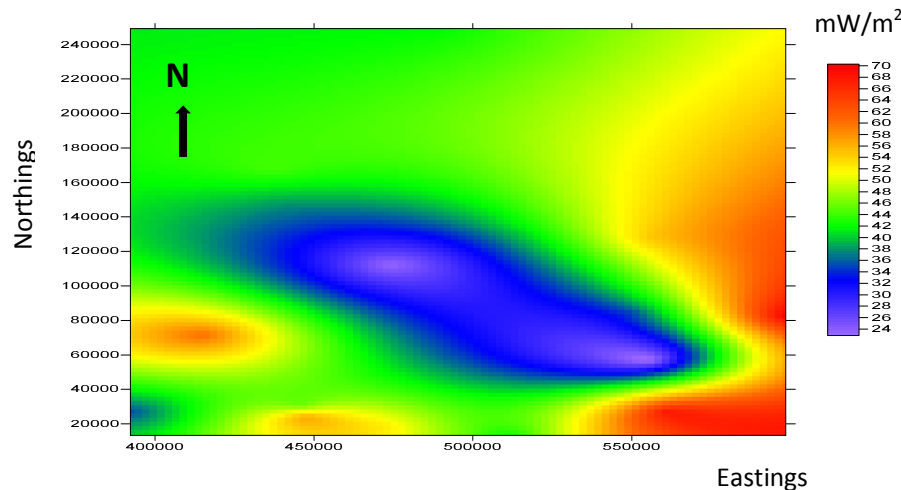


Fig. 9: Heat flow map calculated using ordinary kriging algorithm.

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 results show that the median and the mean are almost the same values. 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 6 and 7, a linear model was fitted to the two variograms respectively. The variograms models have no nugget effects because they started from the origin. The variance of the geothermal gradient and heat flow are 25.705 and 193.77 respectively. These value of variances are assumed to be the values of the sill of the geothermal gradient and heat flow in the study area.

The estimated geothermal gradient in the study area from the ordinary kriging ranges from 18 to 33°C/km, with an average value of 25.5 °C/km. The distribution of the geothermal gradient shows that the southern region is associated with high value and low values. The western and eastern parts have low and moderate geothermal gradient respectively. The estimated heat flow from the ordinary kriging analysis in the study area ranges from 24 to 70 mW/m², with an average of 47.0 mW/m². The highest heat flow occur in the eastern and parts of the southwest region. Moderate heat flow is present in the northern and partly in the southern regions. The lowest heat flow which trend in the northwest – south east directions is found in the central region of the study area. The low heat flow may be attributed to high sedimentary thickness. 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. Furthermore, the heat generation from radioactive activities is very low. The estimated

geothermal gradient and heat flow are in agreement with the values obtained in other tectonically stable and inactive regions of the world. 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 area 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 has 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. Linear models were used for the spatial variation of the geothermal gradient and heat flow variograms. 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. Linear 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 and analysis of the tectonics activities in the study area.

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