

Review paper

SPATIAL VARIATION MODELING (Modeling or Modelling ? Choose 1 spelling and keep it for all the text) 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 geothermal data in the study area (Which area ? You need to be more precise here) 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 (Modeling or Modelling ? Chose 1 spelling and keep it for all the text) 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 70mW/m. 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 (Do a table and put all the results in a table) respectively (Which Units ? , Give the units of all the numbers you put). The results showed that the median and the mean are almost the same values (So what can we expect from theses results ?). 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 (You need to do a table to put all the result with unit in a table). 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 (Same thing, add a table and put all your results and give explanation). 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. (Same thing, put all your values in a table and explain the results) These value 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 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

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44 The Niger Delta is one of the major sedimentary basins and the only discovered
45 hydrocarbon bearing (for now) in Nigeria. ([Show a geological map of the Niger delta basin,](#)
46 [description of the Basin with all geological features and localisation..or refer to it](#)) It is
47 ranked among the world major hydrocarbon reserved and it has been known for its large
48 accumulation of oil and gas. As a result of the abundance of oil and gas in the region,
49 exploration and exploitation works ~~started have been on for about fifty years now~~ [fifty years](#)
50 ~~ago and several geothermal studies on the geothermal regimes of different parts of the~~
51 ~~basin have been carried out done~~

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52 Many geoscientists([Give the lists and some references](#)) have computed the geothermal
53 gradients and heat flow of the Niger Delta. According to ~~[1]~~ [\(write the names of the autors](#)
54 [here and reference](#)) the heat flow of the northern Niger Delta sedimentary basin varies
55 between 38.70 mWm^{-2} and 64.28 mWm^{-2} with an average of 51.49 mWm^{-2} . The geothermal
56 gradients of the Niger delta computed from well log by ~~[2]~~ [\(write the names of the authors](#)
57 [here and reference](#)) 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
58 northern part. ~~[3]~~ [\(write the names of the authors here and reference\)](#) computed the
59 geothermal gradient and heat flow in parts of the eastern Niger delta from 71 wells and
60 obtained geothermal gradient varying between 12 to $24^{\circ}\text{C}/\text{Km}$ with an average of
61 $17.6^{\circ}\text{C}/\text{Km}$ 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
62 the shallow offshore. They also observed heat flow values ranging from 29 to 55 mWm^{-2}
63 with a mean of 42.5 mWm^{-2}

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64 . The geothermal gradients and heat flow values in the distal part of the Niger delta varies
65 between $19\text{--}32^{\circ}\text{C}/\text{Km}$ and $45\text{--}85 \text{ mWm}^{-2}$ respectively [according to \(Write the authors name](#)
66 [here\)](#) [4]. Anomohanran⁵ [\(use the same reference style\)](#) obtained geothermal gradients
67 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
68 values ranging from 38.93 to 89.59 mWm^{-2} in parts of Delta state, Nigeria.

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69 Geothermal gradient and heat flow spatially vary from place to place. Geostatistics make use
70 of statistical tools for incorporating the spatial locations of observations in data processing,
71 allowing for description and modelling of spatial patterns and estimation at unsampled
72 locations [6, 7]. The accurate prediction of subsurface geothermal data spatial distribution is
73 very important. ~~(Therefore, there is need to model the spatial variation of the geothermal~~
74 ~~data in order to be sure of the accuracy of the data when using them for sedimentary basin~~
75 ~~modelling, analysis of crustal tectonics and hydrodynamics, hydrocarbon maturity,~~
76 ~~generation and migration and for hydrothermal resource investigation.)~~ [\(Reformulate\)](#) One
77 ~~technique~~ [technique](#) that can be used to assess the spatial variation of geothermal data is
78 geostatistics. This research ~~is concerned with~~ [focus on](#) the modelling of the spatial variation
79 of geothermal gradient and heat flow in the study area [\(You need to explain Clearly why](#)
80 [you made this study ? what will be the impact?\)](#). The ~~model variogram~~ [variogram model](#) of
81 the data was used for the Kriging estimation techniques.

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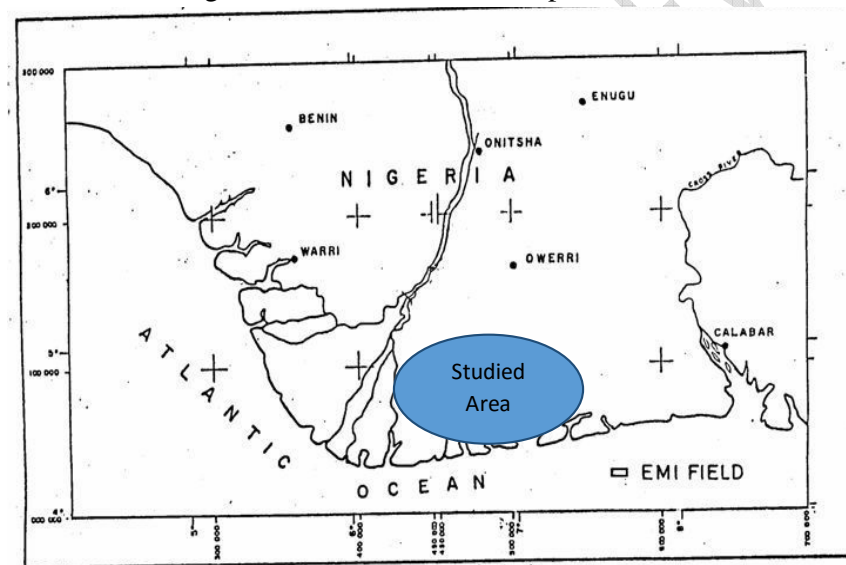
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Geostatistical methods analyze random events in terms of their spatial characteristics. They provide tools for explaining spatial continuity and the possibilities of regression models by incorporating spatial continuity in the model (add references here). These methods are 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.~~ (Should be in the same format like the title 1.)

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 been discussed by many researchers (give the name and then references) [10, 11]. The Niger Delta is one of the most prolific areas in the world [12].



(The map is not readable, we can't see anything, add x and y labels.)
Find a clear geological description of the map...

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

Three lithostratigraphy are present in the Niger Delta. The lithostratigraphy are Benin, Agbada and Akata Formations (We want to see it clearly on the map, it is not visible). Hydrocarbon accumulation in the Niger Delta is confined to the Agbada formation [13]. The uppermost section is the continental deltaic plain

sands which is known as the Benin Formation. The Benin Formation is underlies by the Agbada Formation which is made up of alternation of sand and shale. The basal Akata Formation is made up of marine prodelta shale. Majority of the hydrocarbon accumulations in the Niger Delta occur in the Agbada Formation. (Also find a vertical profile of your map or area of study...with explication)

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. (Add References please ..where did you get those informations)

3. METHODOLOGY

The basic data used for this work are geothermal gradient and heat flow data obtained from 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 (References). 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 (which values ? maximum and minimum ?) 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.~~

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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~~ are 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 are calculated. (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.

3.2 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(Add references). It ~~explain~~explains the variance in variable values due to differences in spatial locations of the analysed parameters. The semi-variogram is a function that provides half the variance of the continuity between all points separated by h (what 's h represent here ?)and is inversely proportional to the distance of points in spatial analysis. The semi-variogram which is half the variogram is commonly usedfor modeling spatial distribution of data. The semi-variogram can be ~~obtain~~obtained with the equation[15, 8]: (add the number of the equation below)

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

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.

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3.3 Kriging Analysis

Kriging techniques provides the best linear unbiased estimators of the value oftheanalyzed 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 (add references). The kriging methods are ~~applied~~used to estimate the~~unknown~~ values of the analyzed phenomenon in a given location based on measurements (observations) performed at several ~~points with~~known coordinates points. The kriging interpolation was calculated as a linear combination of regionalized random variables asshown in the equation N:(Add the number of the equation)

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

where:

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

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

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

175 4.RESULTS AND DISCUSSION

176 The spatial distribution of geothermal gradient and heat flow computed from
177 available bottom-hole temperatures are shown in Figs. 2 and 3. These
178 geothermal data were used for geostatistical ~~the~~ study. The geothermal
179 gradient and heat flow data were checked for (??outliers ?? what do you
180 mean here ?) such that the data below and above certain range were removed
181 from the datasets before the geostatistical analysis was applied. These
182 extreme values probably are the result of measurement or notation errors and donot represent
183 the real thermal conditions. (this part is a quality check, show the data you removed in a
184 graph, you have toplot the graph here) A total of 18 datasets were used for the
185 geothermal gradient and heat flow spatial analysis respectively. (How many
186 points , data do you removed ? compared to the 18 points you used for your
187 analysis...Only 18 points ? I am afraid it is not enough...could you have
188 more point for your kriging method ?)

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189 The histograms generated for the geothermal gradient and heat flow are
190 shown in Figs 4 and 5. The summary of the statistical analysis of the two
191 datasets is shown in Table 1. (Update your table number...Remember you need
192 to create more tables in the beginning). These statistics were used to evaluate a
193 model and find ~~its~~ it's the optimal parameters for the semivariogram.

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194 Figs. 6 and 7 show the computed experimental semi-variograms of the geothermal gradient
195 and heat flow of the area. In both cases, the semi-variogram values increase with the
196 separation distance, reflecting that the geothermal gradient and heat flow values close to each
197 other are more alike, and thus their squared difference is smaller, than those far apart. The
198 model variograms were used for generating the ordinary kriging maps of the geothermal
199 gradient and heat flow (Figs 8 and 9) respectively. (You need to justify why you used a linear
200 Variogram model here.. you can use different variograms model,, and compared the results
201 here. Put in a table the results of the different kriging errors (estimate errors..variance
202 obtained) by comparing to with different models..exgaussians, spheriques or other, (you can
203 also have a combinaison of spherique+ Linear or gaussian + Linear...) You need to find the
204 Best one...I can also see a nugget effect here...
205 You need to justify your choice of the linear model. I am afraid it is not the best choice...you
206 have to prove it...)

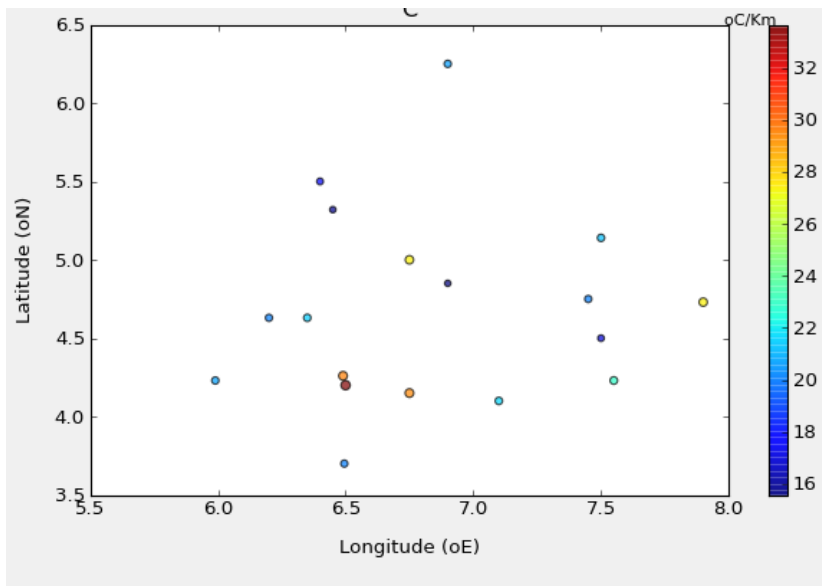


Fig. 2: Base Map of the Study Area Showing the Geothermal Gradient Values ($^{\circ}\text{C}/\text{Km}$)

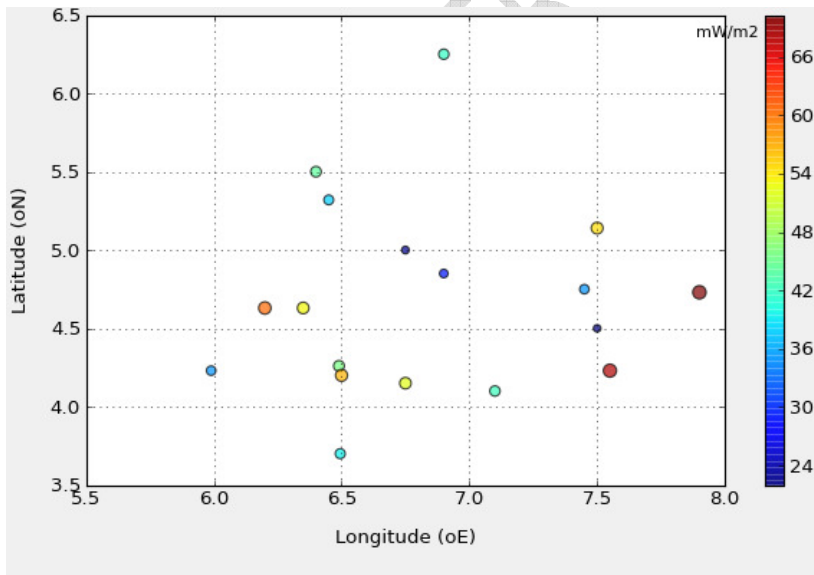


Fig. 3: Base Map of the Study Area Showing the Heat Flow Values (mW/m^2)

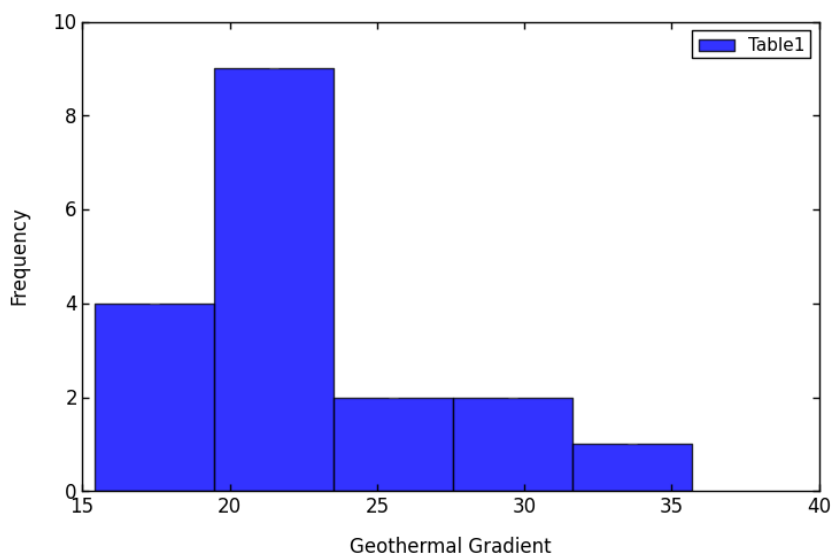


Fig. 4: Histogram of the Geothermal Gradient ([add unit on Label](#))

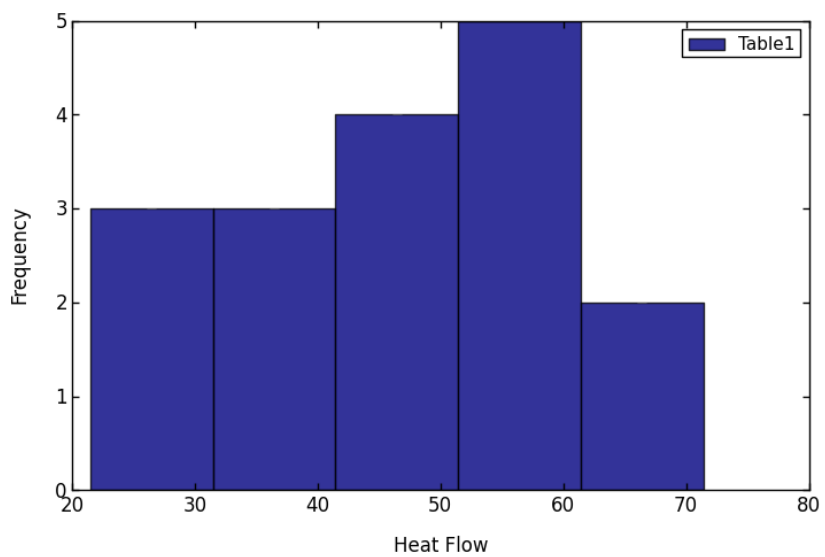


Fig. 5: Histogram of the Heat Flow ([Add Unit on X Label](#))

Table 1: Summary of Computed Geothermal Gradient and Heat Flow Statistics [\(Add unit in the table\)](#)

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

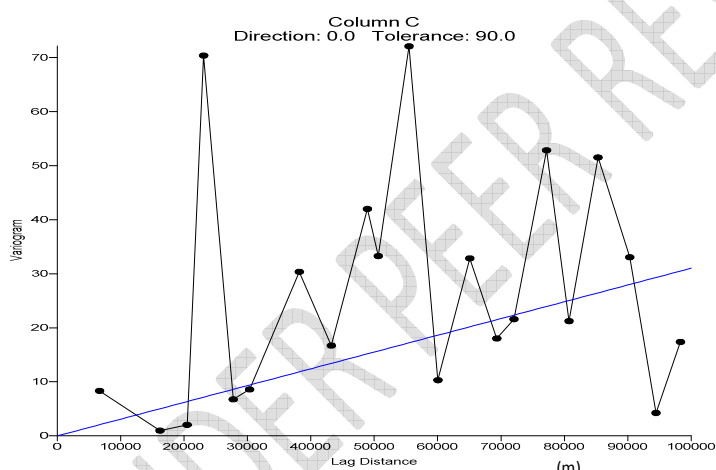


Fig. 6: Computed variogram and variogram model for geothermal gradient. [\(The Linear Model here is not necessary the Best choice..You have to prove it..it can be a mixt of 2 model ..linear +.or other you have to find it or prove or justify your choice\)](#)

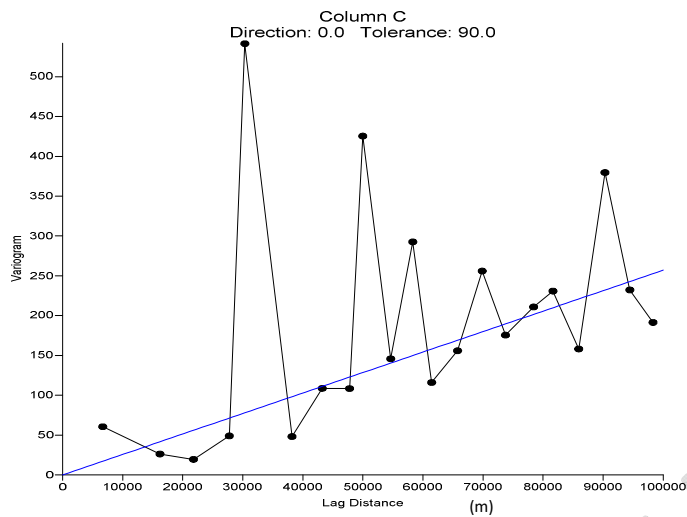


Fig. 7. Computed variogram and variogram model for heat flow (I can see a nugget effect here...find a good mix of variogram here...or prove you have the best choice of model..for example thing about a (nugget effect + Gaussian variogram)...and compare the results with your linear model)

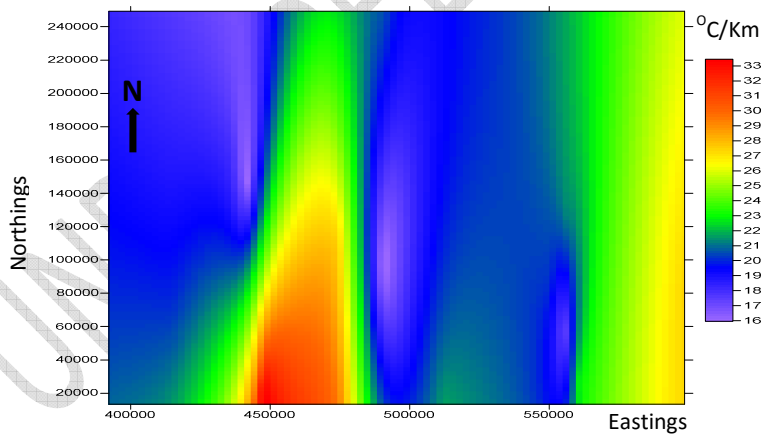


Fig. 8. Geothermal gradient map calculated using ordinary kriging algorithm

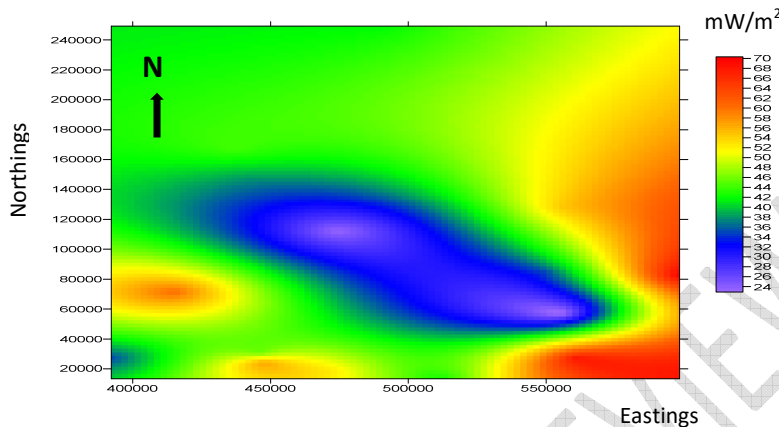


Fig. 9: Heat flow map calculated using ordinary kriging algorithm.

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 (What does this mean?). 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. (You need to compare your result with what exist in the literature of other similar field or study.) Are your data (minimum or maximum are physically realistic?)

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. (Not sure ..i can see a nugget effect..prove that you have right...) The variance of the geothermal gradient and heat flow are 25.705 and 193.77 respectively. These value values 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-occurs~~ flow occurs 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 (References ? interpretation ?). Generally, the heat flow increases toward the eastern region.

(Add a new part here : Interpretation of the results)

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 (Which one ? name and references...). 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 (??? Add references) 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

Rewrite the conclusion after you do all the modifications...

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 (I can't see anywhere the kriging errors ? how can you be sure that you have the best model...). The geostatistics modelling show spatial distribution models and spatial dependence levels of the geothermal data. Linear model was fitted to the computed variograms (need to be prove that is the best model...). 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 [\(why is it important ?\)](#).

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