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Determination of the Heat Flow in the Sokoto Basin, Nigeria using Spectral Analysis of Aeromagnetic Data

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Abstract

In this study, the Determination of heat flow in the Sokoto Basin North Western Nigeria using spectral analysis of aeromagnetic data was carried out. The study area is bounded by latitude 11.0°N to 13.5° N and longitude 3.5°E to 6.5°This research is necessitated by the need for renewable alternative sources of energy for use in Nigeria. Depth estimates were made from the spectral analysis of the magnetic anomalies. The Upward continuation filter control was utilized to suppress the short wavelength components in the Sokoto Basin. The continuation was carried out at various heights (2km, 5km, 10km, 15km and 20km). The centriod depth which relates to the point where magnetism is lost in the crust was calculated using the rate of decay of the spectrum. The results from **s**pectral analysis suggested that in the Sokoto basin the basement is deepest at the north eastern portion toward Niger Republic and varies between 0.61 and 1.54km, while the centriod depth varies from 6.35 to 13.05km. It also suggested that basin is underlain by a Curie-point isotherm of between 11.36 to 22.30km and corresponding gradient and heat flow values varying from 26.18 to 44.62^0 C/km and 52.36 to 98.57mW/m^2 respectively. The maximum heat flow is found around the central area (i.e around Tambuwal). The average heat flow in normal continental region is about 60mW/m^2 , values between 80 and 100 mW/m^2 are good geothermal sources while values greater than hundred is an indication of anomalous condition. Anomalous and good high heat flow for good geothermal sources was observed in the area. These areas with high heat values may be good geothermal sources and therefore are recommended for further investigation.

Keywords: Aeromagnetic, spectral energy, geothermal gradient, Curie point, sedimentary

1. Introduction

In this study the total field aeromagnetic anomalies for the Sokoto basin was evaluated for the estimation of the heat flow in the area using spectral analysis. Despite the fact that geological surveys in the "Sokoto Basin" dates back to the 1800's, geophysical surveys started at about 1930 and has since then has received limited geophysical attention. The preliminary geophysical surveys were targeted at the water resources within the basin. Nigeria is one of the biggest producers of oil and gas in the world; hydrocarbons are the major source of general energy productions. However, general problem within Nigeria energy sector has made the authority to search for some other solution, including the alternative source of energy. During the last decade, when the development in technology of renewable clean energy use has been spreading worldwide, the awareness of energy sector as well as federal and local authorities on renewable energy rose also in Nigeria. The basin has no record of crustal temperature studies; therefore the assessment of heat flow in the basin will compliment the geophysical information of the adjoining basins to the gap of missing crustal information in the northern Nigeria.

Bhattacharya,(1966), Spector and Grant (1970) and Clement (1973) has explained a two dimensional (2-D) technique for spectral analysis of aeromagnetic anomalies. An expression for the power spectrum of the total magnetic field intensity over a single rectangular block was derived by Bhattacharya (1966) and was generalized by Spector and Grant (1970) Megwara *et al.* (2013) and by assuming that the anomalies on the aeromagnetic map are due to an ensemble of vertical prisms. The demonstrated that the contributions from the depth, width and thickness of magnetic source ensemble could affect the shape of the energy spectrum and the depth factor is the main term that controls the shape. The depth estimates could be calculated using the equation below (Spector and Grant, 1970, Hahn et al., 1976).

$$E(r)=\exp(-2hr) \tag{1}$$

Where E(r), h and r are the spectral energy, mean depth and frequencies respectively.

The linear segments are located from the plot of the logarithm of the energy values versus frequency on a linear scale. Each linear segment group point is due to anomalies caused by the bodies occurring within a particular depth. The gradient of the linear segment is therefore evaluated.The equation of spector and Grant, (1970) below is used to determine the depth to causative body.

$$h=-m/4\pi \tag{2}$$

Where m is the gradient.

In 1970 Spector and Grant also showed that another factor, (1-e^{-tr})^2 contributes thickness in the energy spectrum; where, t is the thickness. Smith *et al.*(1974) and Boler (1978) used the effect of the factor to find the thickness of the deepest magnetic layer. The parameter t, plays an interesting role in shaping the power spectrum. For no too large values of r, when combined with the depth factor e^{-2hr} the effect of $(1-e^{-tr})^2$ produces a peak in the spectrum whose position shifts towards smaller wave numbers with increasing values of t. when this peak occurs (significant maximum), it indicates that the sources bottoms are detectable.

Whether the source appears to be depth limited or not depends very much on the size of the map. If there were no restrictions upon either the size of the map or size of the computer, then the curie-point isotherm could be observed.

From the slope of the power spectrum, the top bound and the centriod of a magnetic layer are determined. The base depth of the magnetic source is:

$$h_c = 2h_3 - h_2 \quad (3)$$

Where h_3 is the centriod of the magnetic layer

h_2 is the top bound

The obtained base depth h_c of the magnetic source is assumed to be the curie-point depth

Heat flow estimates on the crust may therefore be made using the depth and thickness information. The Curie point temperature at which rocks loss their ferromagnetic properties provides a link between thermal models and models based on the analysis of magnetic sources.

The magnetic susceptibility and strength of the material that make up the continental crust are controlled by the temperature. At temperature higher than the curie point, magnetic ordering is loose and both induced and remanent magnetization disappear, while for temperatures greater than 580°C those material will begin to experience ductile deformation. The basic relation for conductive heat transport is Fourier's law. In one-dimensional case under assumption that the direction of the temperature variation is vertical and the temperature gradient (dT/dz) is constant; Fourier's law takes the form:

$$q = - k\, dT/dz \quad (4)$$

where, q_z is heat flow and k is thermal conductivity.

The Curie temperature θ_c can also be defined as:

$$\theta_c = (dT/dz)d$$

Where, d is the curie-point depth (as obtained from the spectral magnetic analysis).

The surface temperature is 0^0C and dT/dz will remain constant provided there are no heat sources or heat sinks between the earth's surface and the curie-point depth,. The Curie temperature depends on magnetic mineralogy. For example although the curie temperature of magnetite (Fe_3O_4) is at approximately 580°C, an increase of titanium (Ti) contents of titanomagnetite ($Fe_{2-x}Ti_xO_3$) will causes a reduction of the curie temperature. A curie-point temperature of 580°C and thermal conductivity of $2.5Wm^{-1}°C^{-1}$ which is the average thermal conductivity for igneous rocks is used in the study as standard (Nwankwo *et al* 2009).

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2. Geology of the study Area

Sokoto Basin north-western Nigeria (fig1) is part of the South Eastern sector of the Iullemmeden basin. It is bounded by latitudes 11.0° North and 13.5° North and longitudes 3.5°East and 6.5° East (fig 2).

The Basin is one of the young (Mesozoic – Tertiary) inland cratonic sedimentary basin of West Africa Mc Curry (1976), Shehu *et al., (*2004) and Obaje (2009). The basin like other intra-continental basins of the region and African continent in general developed by epeinogenic warping of stretching and rifting of technically stabilized crust. These movements commenced around the beginning of the Paleozoic and continued upper cretaceous and more responsible for the south western propagation of sediments deposited within the basin (fig 2), Kogbe (1979 and 1981), Wright *et al*., (1985).

The basin consists predominantly of a gentle undulating plain with an average elevation varying from 250 to 400 meters above sea level (Kogbe, 1979).The area is marked by two distinct climatic conditions; the rainy and dry seasons. The average rainfall ranges from 1,115mm in the extreme southeast, to 734mm at Sokoto. The rainfall is concentrated in a short wet season which extends from mid May to mid-September, whilst the dry season lasts for more than seven months. November to March/April being particularly dry and no single drop of rain may fall.

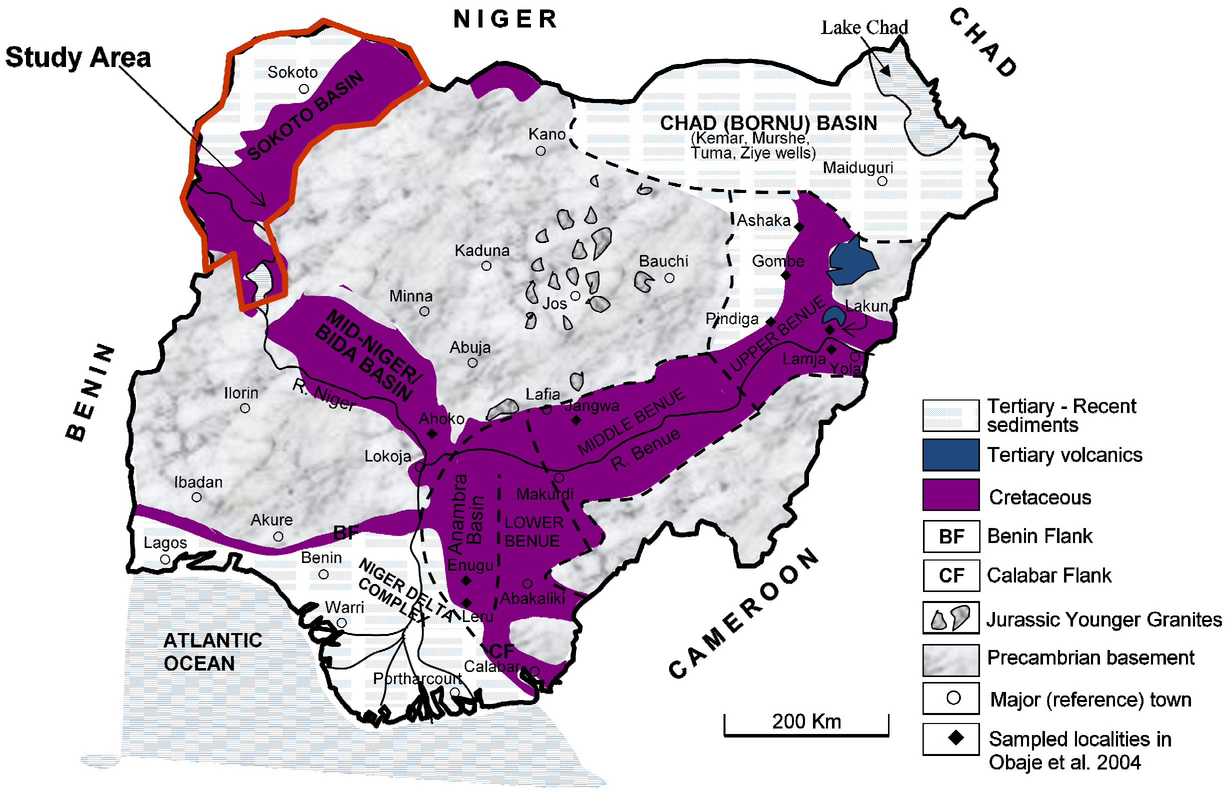


Fig 1:Sketch geological map of Nigeria showing the location of the Sokoto Basin within the inland basins of Nigeria

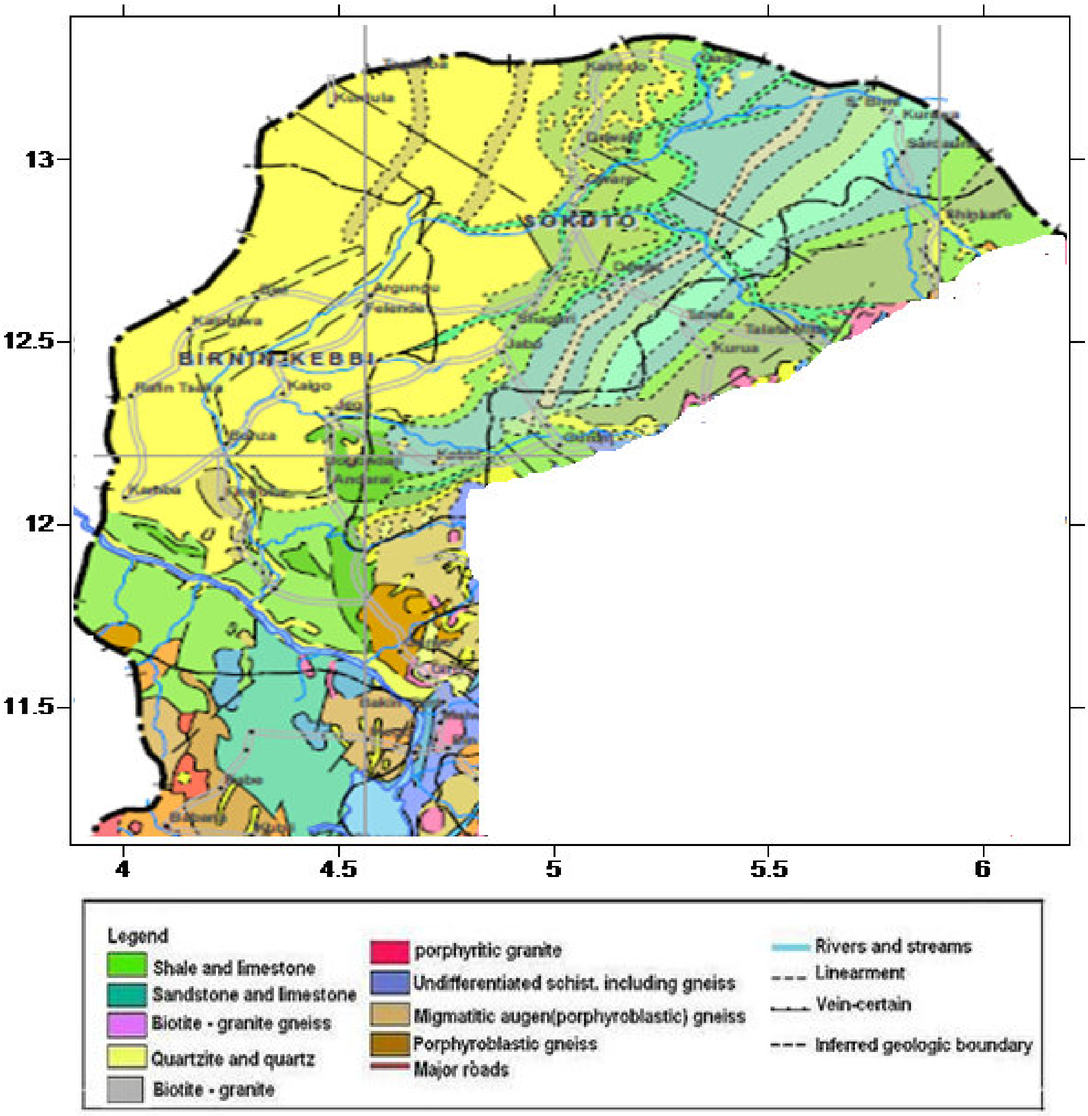


Fig2: Geological sketch map of the Sokoto basin (south-eastern sector of the Iullemmeden) (Adapted from Geology map of Nigeria produced by the Geological Survey Agency of Nigeria, 2006).

March/April being particularly dry and no single drop of rain may fall. The dry season is usually heralded by dry cold Harmattan wind coming from the desert and is always dust laden, such that stationary objects are quickly covered by dust whilst visibility is greatly impaired by a haze of dust particles.

The sedimentary rocks of the basin composed of sandstone, limestone and clay of cretaceous to tertiary ages from a multilayered groundwater basin with pumping rate of 300/min at a well with 100-150mm in diameter Adetona *et al,.(*2007) . The alluvia in Fadama also contain unconfined groundwater. The Sokoto basin in Nigeria, like sedimentary basin in other parts of the world provides possible source rocks, reservoir beds and the structural environment required for hydrocarbon accumulation.

3. Materials and Methods

Twenty eight airborne magnetometer survey maps of contours of total magnetic field intensity of sheet numbers 8-13, 26-32, 48 -54, 71-74, and 94- 97 published by the Geological Survey of Nigeria (GSN) agency (now Nigerian Geological Survey Nigeria Agency, NGSA), on a scale of 1:1000,000 were used as basic data for determining the nature of magnetic anomalies over the study area. The contour interval is variable at 5, 10, 25 and 50 nT. The survey was carried out along a series of north to East lines with a spacing of 2km and an average flight elevation of 152.4m above the ground level.

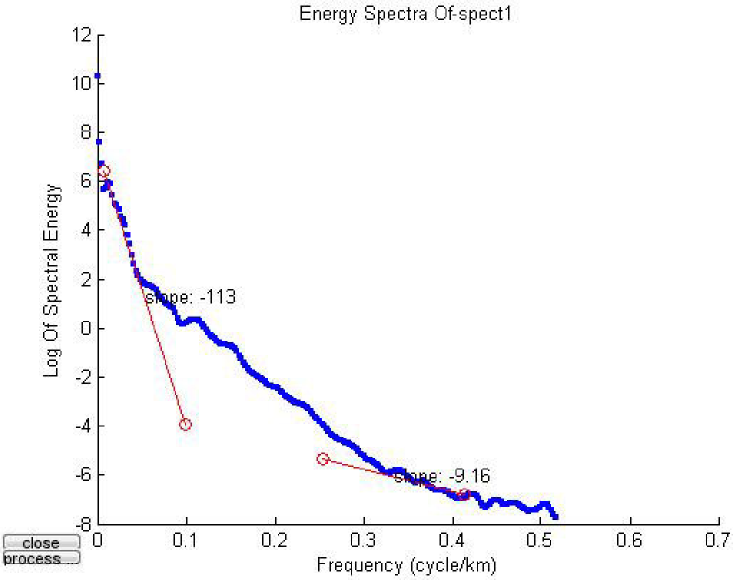
A computer program Oasis Montaj was used to derive the residual magnetic values by subtracting values of the regional fields from the total magnetic intensity values at the grid cross point. Short wavelength components of the residual anomalies were filtered out by applying upward continuation technique. The continuation was carried out at 2km, 5km, 10km, 15km and 20km

The residual map of the study area was divided into twenty six (26) blocks of overlapping sections. Graphs of logarithms of the spectral energies against frequencies estimated for various blocks were obtained. Linear segment from low frequencies portion of the spectra, representing contributions from the deep seated causative bodies could be drawn from each graph. The gradient of the linear segment was evaluated and the equation 2 was used to calculate the depth to causative bodies (Figure 4). Equation 3 was subsequently used to calculate the curie-point depth (Figure 6).

4. Results and Discussion

Graphs of logarithms of the spectral energies against frequencies estimated for various blocks were obtained. The graphs of the logarithm of the spectral energy against frequencies for blocks 1 and 2 are shown in fig 3a-b.The occurrence of a significant peak in the spectrum indicates that the curie-depth, which define the source bottoms, are detectable.The results from depth analysis suggested that the top bound layer ranges between 0.61 – 1.54km (Figure 4) .This is the depth to the top of basement and represent the thickness of the sediment in the area and is deepest at the north eastern portion toward Niger Republic (Figure 5).

The centriod depth is the depth that relates to the point where magnetism is lost in the crust (Nafiz, 2009).The estimated depth reveals an undulating depth which varies from 6.35 in the south western portion to10.03km in the Rabah area and 13.03km in the Donko area (Figure 6), while the curie- point depth varies from 11.36 – 22.30km and increases from the northern to the southern parts of the map (Figure 7). Curie point was found to be deepest at the south- western portion of the study (Figure 8). Using a curie-point temperature of 580^0C and the derived curie-point depth, geothermal gradient variations in the area were obtained and shown in Figure 9; thermal conductivity of 2.5 $Wm^{-1}\ {}^0C^{-1}$ (Nwankwo *et al.*2009) was subsequently used to estimate the corresponding heat flow anomalies in the study area.



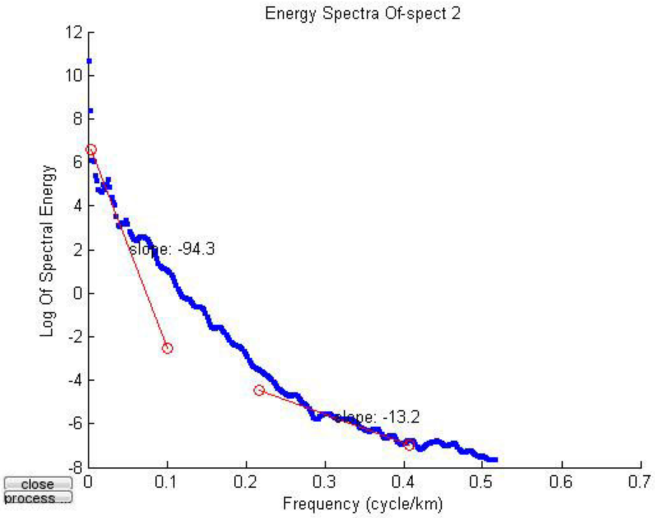
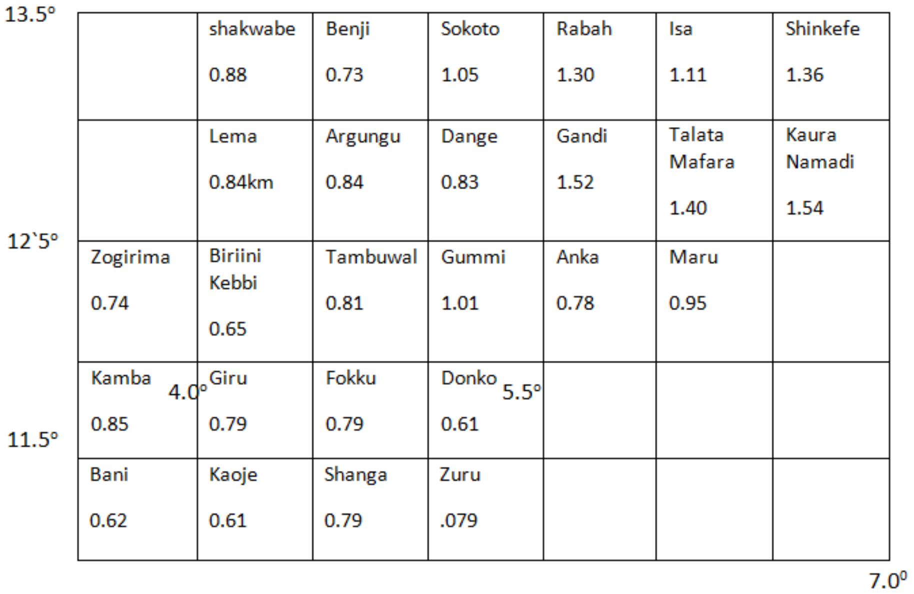


Figure 3 a and b : Power Spectra for Depth Estimation for blocks 1 and 2



	shakwabe 0.88	Benji 0.73	Sokoto 1.05	Rabah 1.30	Isa 1.11	Shinkefe 1.36
	Lema 0.84km	Argungu 0.84	Dange 0.83	Gandi 1.52	Talata Mafara 1.40	Kaura Namadi 1.54
Zogirima 0.74	Biriini Kebbi 0.65	Tambuwal 0.81	Gummi 1.01	Anka 0.78	Maru 0.95	
Kamba 0.85	Giru 0.79	Fokku 0.79	Donko 0.61			
Bani 0.62	Kaoje 0.61	Shanga 0.79	Zuru .079			

Figure 4: Estimated values of top bound source, h_2 in km and their respective sheet numbers

The result shows that geothermal gradient varies between 22.18 and 44.62^{o}C/km (Figure 10). The corresponding heat flow values vary from 52.36 to 98.57mW/m2 (Figure 11). The heat flow in the study area has a general trend which is not a horizontal surface but an undulating surface. The maximum heat flow is found around the Tambuwal area (Figure13).

All current literature states that the curie-point depth and heat flows greatly depend on geological conditions. In geothermal exploration heat flow is the primary observable parameter. Generally high heat flow values correspond to volcanic and metamorphic region since theses two units have high heat conductivities. Additionally, heat flow is significantly affected by tectonically active regions (Tanaka *et al.,* 1999).

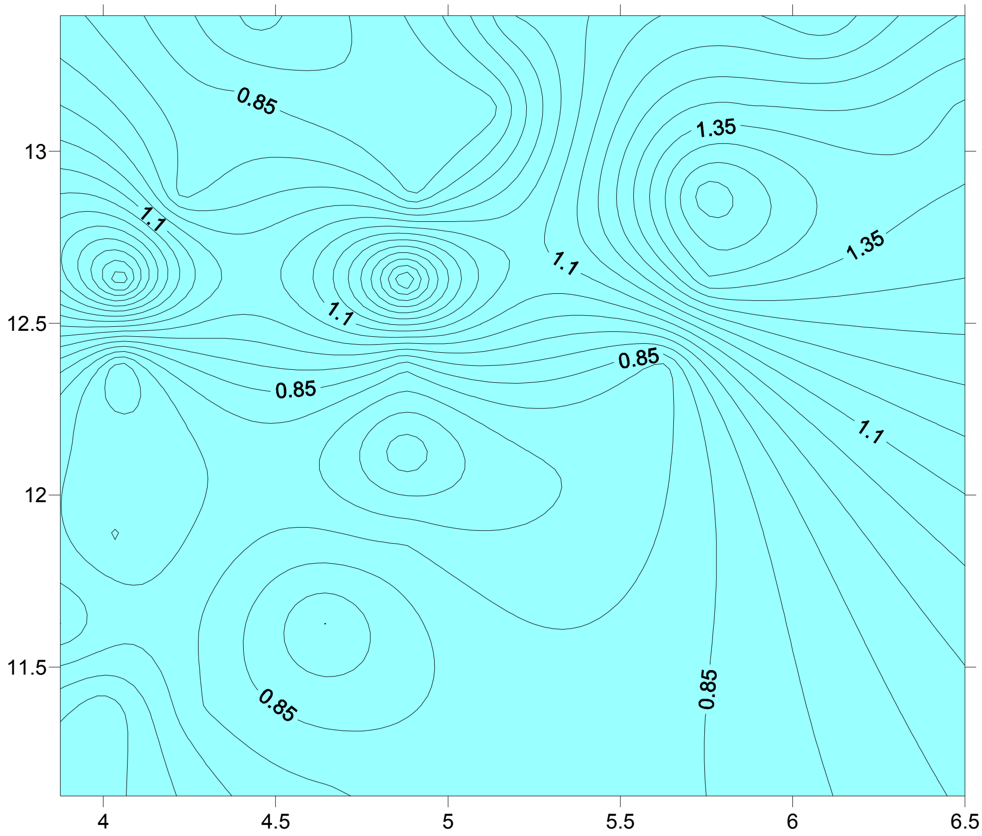


Fig 5: Contour map of the top bound source h_2 contour interval 0.05km. x-axis and y-axis are longitude and latitude coordinates in decimal degrees.

13.5°

	Shakwabe 9.31	Benji 8.99	Sokoto) 7.43	Rabah 10.03km	Isa 7.48	Shinkafe 6.92
	Lema 10.74	Arugungul 7.04	Dange 6.72	Gandi 7.38	Talata Mafara 7.48	Kaura Namadi 7.38
Zogirima 10.66	Birnin Kebbi 7.85	Tambuwal 6.10	Gummi 9.31km	Anka 9.63	Maru 9.79	
Kamba 6.35	Giru 6.60	Fokku 10.82	Donko 13.05			
Bani 11.46	Kaoje 7.16	Shanga 11.38	Zuru 10.90			

12.5°
11.5°
4.0° 5.5° 7.0^0

Figure 6: Estimated values of magnetic centriod depth h_3 in km and their corresponding sheet names

Geothermal energy does also occur in areas where basement rocks that have relatively normal heat flow are covered by thick blanket of thermally insulated sediments. It can be inferred that the high heat areas in the study area may be areas where thick blanket of thermally insulated sediments cover basement rocks since there is no evidence of volcanic activities in the study area. In thermally normal continental regions the average heat flow is about 60mW/m^2, values between 80-100mW/m^2 are good geothermal source, while values greater than 100mW/m^2 is an indication of anomalous geothermal conditions (Jessop *et al.,* 1976).

13.5°		Sakwbea 17.43	Benji 17.25	Sokoto 13.91	Rabah 13.65	Isa 17.83	Shinkafe 12.48
		Lema 20.60	Argungu 13.26	Dange 12.62	(Gandi 13.26	Talata Mafara 13.52	Kaura Namadi 17.88
12.5°	Zogirima 20.48	Birnin Kebbi 15.06	Tambuwal 12.32	Gummi 11.36	Anka 18.48	Maru 18.62	
	Kamba 11.85	Giru 12.50	(73) 20.85	Donko 25.50			
11.5°	Bani 22.30	Kaoje 13.71	Shanga 21.97	Zuru 21.01			

4.0° 5.5° 7.0°

Figure 7: Estimated values of Curie depth, h_c in km and respective sheet names

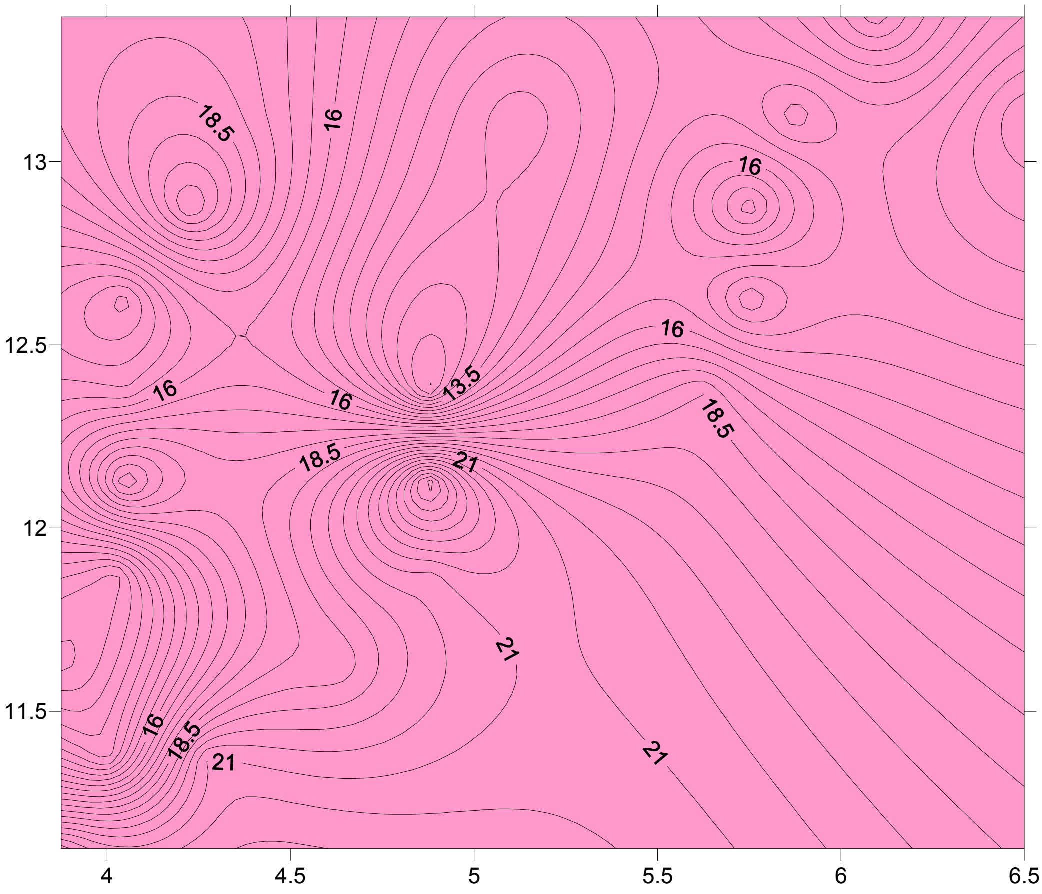
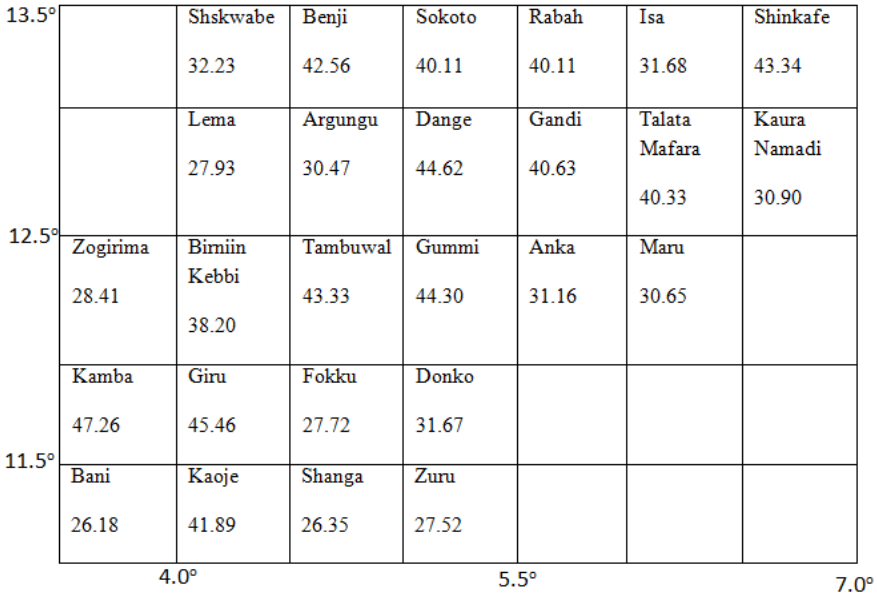


Figure 8: Curie-point isotherm (h_c) map. Contour interval 0.5km. x-axis and y-axis are longitude and latitude coordinates in decimal degrees.



	Shskwabe 32.23	Benji 42.56	Sokoto 40.11	Rabah 40.11	Isa 31.68	Shinkafe 43.34
	Lema 27.93	Argungu 30.47	Dange 44.62	Gandi 40.63	Talata Mafara 40.33	Kaura Namadi 30.90
Zogirima 28.41	Birniin Kebbi 38.20	Tambuwal 43.33	Gummi 44.30	Anka 31.16	Maru 30.65	
Kamba 47.26	Giru 45.46	Fokku 27.72	Donko 31.67			
Bani 26.18	Kaoje 41.89	Shanga 26.35	Zuru 27.52			

Figure 9: Estimated values of geothermal gradient in °C/ km and their sheet names

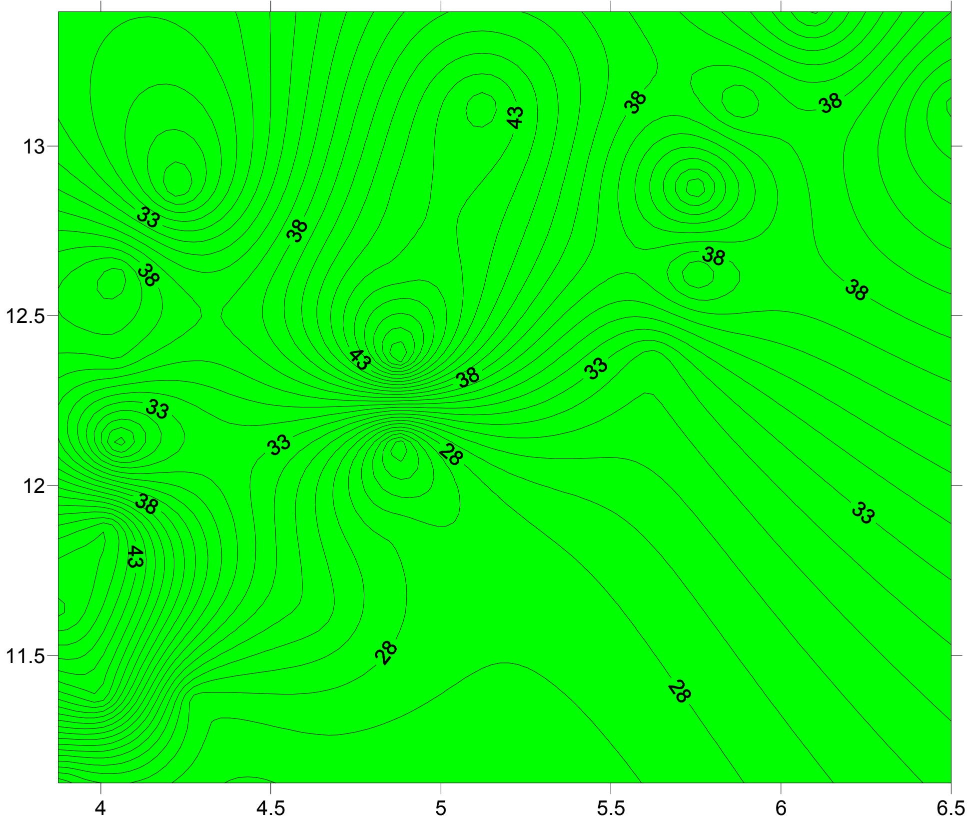
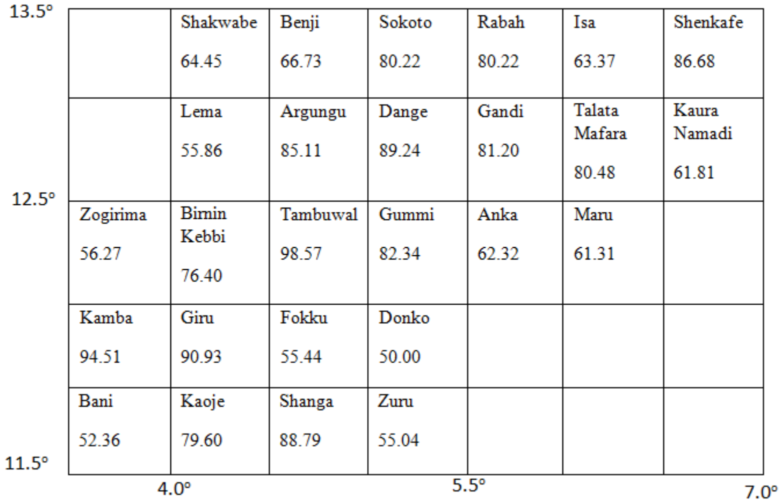


Fig 10: Geothermal gradient map of the study area.(contour interval 0.1°C/km). X-axis and y-axis are longitude and latitude coordinates in decimal degrees.



	Shakwabe 64.45	Benji 66.73	Sokoto 80.22	Rabah 80.22	Isa 63.37	Shenkafe 86.68
	Lema 55.86	Argungu 85.11	Dange 89.24	Gandi 81.20	Talata Mafara 80.48	Kaura Namadi 61.81
Zogirima 56.27	Birnin Kebbi 76.40	Tambuwal 98.57	Gummi 82.34	Anka 62.32	Maru 61.31	
Kamba 94.51	Giru 90.93	Fokku 55.44	Donko 50.00			
Bani 52.36	Kaoje 79.60	Shanga 88.79	Zuru 55.04			

Figure 11: Estimated values of Heat Flow in mW/m^2 and their respective sheet names.

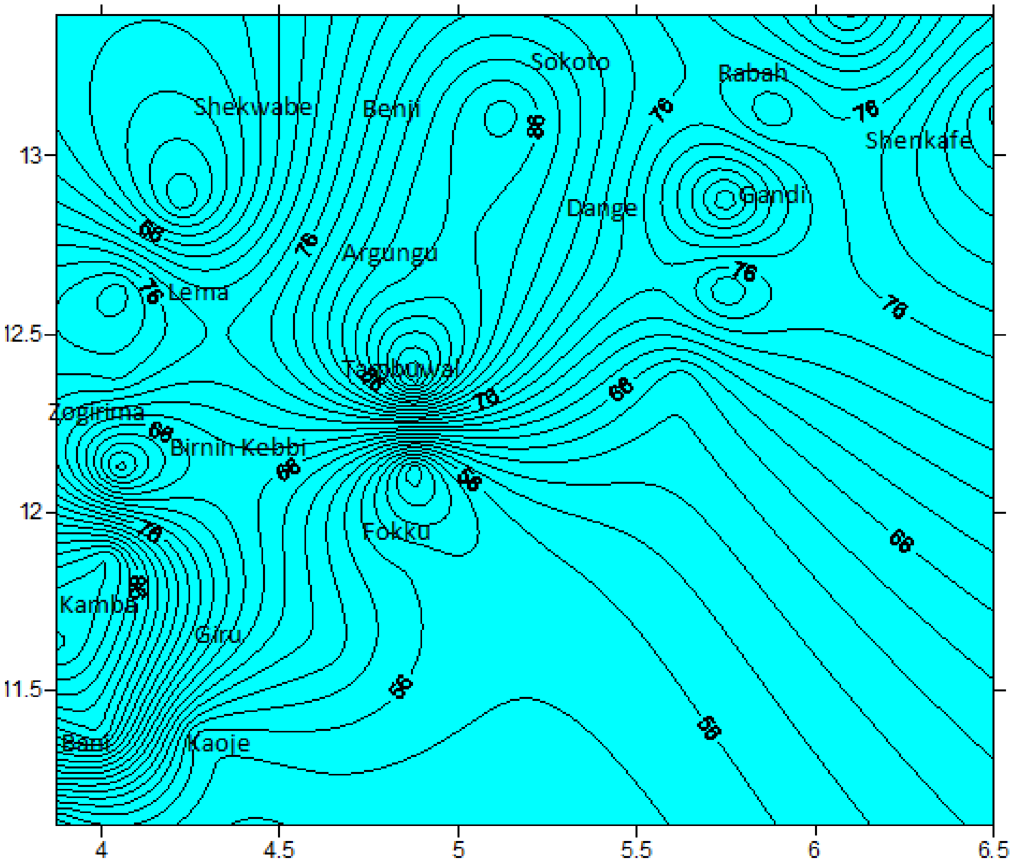


Figure 12: Heat flow map of the study area. Contour interval 2mW/m^2. x-axis and y-axis are longitude and latitude coordinates in decimal degrees.

5. Conclusion

In thermally normal continental regions the average heat flow is about 60mW/m^2, values between 80-100mW/m^2 are good geothermal source, while values greater than 100mW/m^2 is an indication of anomalous geothermal conditions (Jessop *et al.,* 1976). The study area lies within the thermally normal continental regions and good geothermal source.

The high heat that gives rise to geothermal systems are mostly found in the mantle plumes, subduction and rift zones where for unknown reasons large quantities of heat are transported from mantle to the earth crust.

Geothermal energy does also occur in areas where basement rocks that have relatively normal heat flow are covered by thick blanket of thermally insulated sediments. It can be inferred that the geothermal prospect areas in this study may be areas where thick blanket of thermally insulated sediments cover basement rocks since there is no evidence of volcanic activities in the study area, therefore these areas of high heat flow as shown in Figure 11 could be geothermal sources and reservoirs and will be of help in identifying the existence of productive reservoirs at attractive temperature and depth in the Sokoto Basin.

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