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Heat Flow Anomalies from the Spectral analysis of Airborne Magnetic data of Nupe Basin, Nigeria

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ABSTRACT
An estimate of Heat flows in the Northern part of the Sedimentary Nupe Basin, West of Central Nigeria has been made from the spectral analysis of aeromagnetic data. This is in view of increased efforts to explore for new and more energy locations in Nigeria. Airborne magnetometer survey maps covering an area bounded by latitudes 8°30' and 10°00' North and longitudes 4°30' and 6°00' East were used as basic data for determining the nature of magnetic anomalies over the area. The maps were digitised at an equal spacing of 0.875 km, thus imposing a nyquist frequency of 0.57 km^{-1}. Regional anomaly was removed from the digitised data by fitting a plane surface polynomial and upward continuation technique was utilized to suppress short wavelength components of the residual data. The resulting residual data were subsequently divided into 81 overlapped blocks for the purpose of spectral analysis. The result of the analysis show that the geothermal gradient varies between 10 and 45°C km^{-1} while the ensuing heat flows varies between 30 and 120 mW m^{-2}. In the Southeast and Southwest of the study area heat flows were found to be less than 60 mW m^{-2} while flows more than 100 mW m^{-2} are found in the Northeastern and northwestern parts. The average heat flow in thermally normal continental regions is reported to be above 60 mW m^{-2}. Values in excess of about 80-100 mW m^{-2} indicate anomalous geothermal conditions. Anomalous high heat flow values (above 100 mW m^{-2}) have been observed in the study area. Therefore, these areas with such variations maybe recommended for further investigation.

Key words: Aeromagnetic, geothermic, sedimentary, temperature, models

INTRODUCTION
The study presented in this research concerns the evaluation of the total field aeromagnetic anomalies for estimation of Heat flow in the Northern part of the sedimentary Nupe Basin using spectral analysis. The basin, which has in the past received limited attention from geologists and especially geophysicists partly due to lack of immediate geologic and economic values is fast becoming an important study area for geoscientists in view of increased efforts to explore for new and more energy locations in Nigeria. Moreover, geophysical studies in the basin are minimal and with no record of crustal temperature studies. Heat flow assessment of the area would significantly, compliment the geophysical information of the adjoining basins to the gap of missing crustal temperature information of the central part of Nigeria.

Useful two-dimensional (2-D) techniques for spectral analysis of aeromagnetic anomalies have been described by Bhattacharyya (1966), Spector and Grant (1970) and Shuey *et al.* (1977). Bhattacharyya (1966) derived an expression for the power spectrum of the total magnetic field intensity over a single rectangular block, which was generalized by Spector and Grant (1970) by assuming that the anomalies on an aeromagnetic map are due to an ensemble of vertical prisms. They demonstrated that contributions from the depth, width and thickness of a magnetic source ensemble could affect the shape of the energy spectrum. The dominant term, which controls this shape, is depth factor. The depth estimates could be made using the equation (Spector and Grant, 1970; Hahn *et al.*, 1976):

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

where, E(r), h and r are the spectral energy, depth and frequency, respectively.

Graphs of the logarithms of the spectral energies against frequencies are plotted and linear segment from the low frequency portion of the spectra, representing contributions from the deep-seated causative bodies could be drawn from each graph. The gradient of the linear segment is therefore, evaluated and the equation (Spector and Grant, 1970; Hahn *et al.*, 1976) below used to calculate the depth to the causative bodies:

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

where, m is the gradient.

Spector and Grant (1970) also showed that another factor, $(1\text{-}e^{-tr})^2$ 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 a rather interesting role in shaping the power spectrum. When combined with the depth factor e^{-2hr} (for not too large values of r), the effect of $(1\text{-}e^{-tr})^2$ is to produce a peak in the spectrum whose position shifts toward smaller wavenumbers with increasing values of t. When this peak occurs (significant maximum), it indicates that the source bottoms are detectable. The frequency f_{max} of the spectral peak, the mean depth h to the source tops (depth to deep-seated causative bodies) and the mean depth d to the source bottom (Curie depth) are related by (Boler, 1978; Connard *et al.*, 1983; Salem *et al.*, 2000):

$$f_{max} = \frac{1}{2\pi(d-h)} \ln\left[\frac{d}{h}\right] \tag{3}$$

where, d = h + t.

Whether the sources appear 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 presumably the Curie-point isotherm could be observed. Therefore, estimates of heat flows in the crust maybe made using this depth and thickness information. The Curie point temperature at which rocks lose 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 materials that make up the continental crust are factors controlled by temperature. For temperatures higher than the Curie point, magnetic ordering is loose and both induced and remanent magnetization vanish, while for temperatures greater than 580°C those materials will begin to experience ductile deformation. The basic relation for conductive heat transport is Fourier's law. In one-dimensional case under assumptions that the direction of temperature variation is vertical and the temperature gradient (dT/dz) is constant; Fourier's law takes the form:

$$q_z = - k\, dT/dz \tag{4}$$

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

The Curie temperature θ_c can also be defined as:

$$\theta_c = (dT/dz)d \tag{5}$$

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

Provided there are no heat sources or heat sinks between the earth's surface and the Curie-point depth, the surface temperature is 0°C and dT/dz is constant. The Curie temperature depends on magnetic mineralogy. Although the Curie temperature of magnetite (Fe_3O_4), for example, is at approximately 580°C, an increase of titanium (Ti) contents of titanomagnetite ($Fe_{2-x}Ti_xO_3$) causes a reduction of the Curie temperature. A Curie-point temperature of 580°C and thermal conductivity of 2.5 W m^{-1} °C^{-1} as average for igneous rocks is used as standard (Stacey, 1977) in this study.

MATERIALS AND METHODS

Location and geology of the study area: The area of study is bounded by latitudes 8°30' and 10°00' North and longitudes 4°30' and 6°00' East. It is an area of about 27,200 square kilometres situated at the West of Central Nigeria. The Nupe Basin (also known as the Middle Niger Basin or Bida basin) is an elongated NW-SE trending depression perpendicular to the main axis of the Benue Basin of Nigeria. The entire basin is bounded by latitudes 8°00'N and 10°30'N and longitudes 4°30'E and 7°30'E and covers an area of approximately 90 750 km^2 (Fig. 1). The area is marked by two distinct climatic conditions. The rainy season lasts usually from May/June to September/October every year depending on the rainfall pattern for the particular year. The mean annual rainfall is 1560 mm. The dry season is usually heralded annually by the dry, cold Harmattan winds and occurs between November and March. After the departure of the Harmattan and in the absence of rain, the hot sunny season with temperatures exceeding 27°C sets in (Balogun, 2000). The mean annual temperature of the area is 20°C.

The vegetation, which is predominantly of the Savannah-type, is characterised by giant grasses and few trees. Short feathery grasses form an almost continuous ground cover during the wet season. The Niger River and its tributaries mainly water the area. The height above sea level is about 100 m along areas bordering the River Niger and its tributaries but rises to about 200-300 m in other areas. The soil cover in the area is mainly lithosols and alluvial along River Niger areas and its tributaries.

The geology of the Nupe Basin (Fig. 1) is believed to be a gentle down-warped shallow trough filled with Campanian-Maestrichtian marine to fluviatile strata. The strata are believed to be more than 300 m thick (Adeleye, 1973, 1974, 1976). Those with marine affinity, the limestones, often form cappings (under variable thickness of laterites) to the means of the basin. Some form

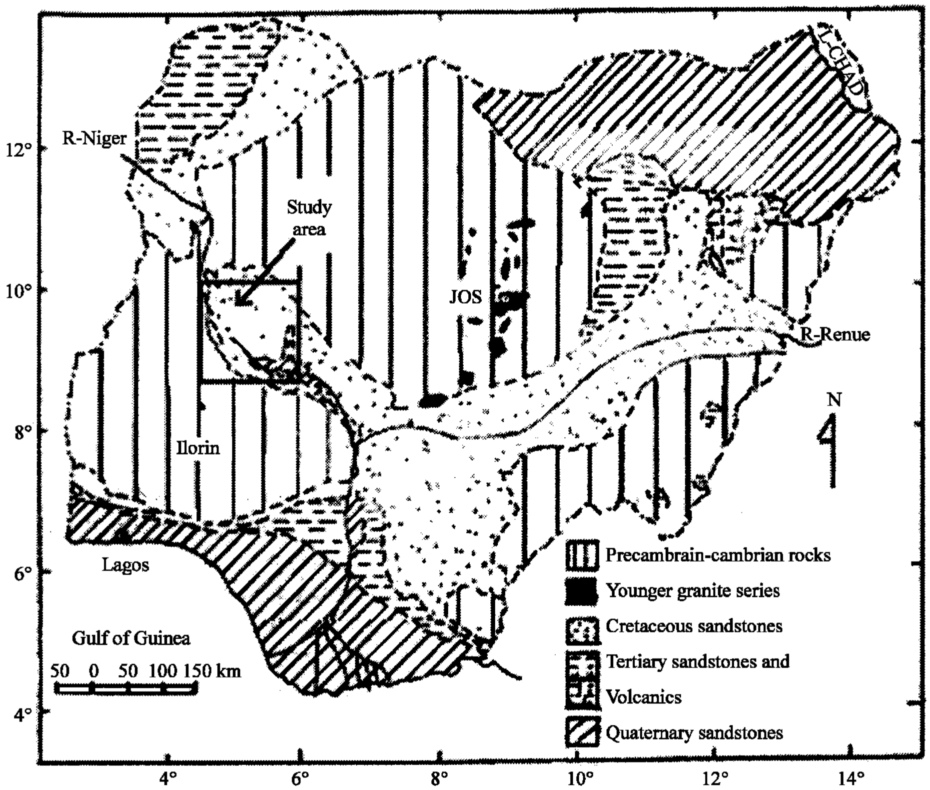

Fig. 1: Geological map of Nigeria showing the surveyed area

prominent intermediate breaks of slope along the mesa walls. Murat (1972) reported that the basin might be regarded as Northwestern extension of the Anambra basin, which is found in the Southeast, both of which were major depocenters during the second major sedimentary cycle of Southern Nigeria in the Upper Cretaceous time.

Data acquisition and analysis: Airborne magnetometer survey maps of contours of total magnetic field intensity of sheets 160, 161, 162, 181, 182, 183, 202, 203 and 204 published by the Geological Survey of Nigeria (GSN) Agency, Airborne geophysical series (1976) on a scale of 1:1000,000 were used as basic data for determining the nature of magnetic anomalies over the area. The contour interval is variable at 5, 10, 25 and 50 nT. The survey was carried out along a series of North-South lines with a spacing of 2 km and an average flight elevation of 152 m above the ground level. The average magnetic inclination across the survey area was from 9° in the north to 0° in the south. Since one common problem in automated data interpretation is to select digitisation spacing and minimum length of data profile in order to minimize aliasing error, selecting a digitisation interval of 0.875 km is found to solve the problem in this study (Khurana, 1981). Therefore, the maps were carefully hand digitised at an equal spacing of 0.875 km yielding 4096 values per sheet and 36,864 values for the 9 sheets used in this study. Although hand digitisation is the most elementary and least efficient method of digitisation, its accuracy when carefully done, compares favourably with other more sophisticated methods (Bath, 1974). The spacing interval of 0.875 km imposes a nyquist frequency of 0.57 km^{-1}.

In view of the simplicity in the trend of the magnetic field in the survey area, the regional anomaly was removed from the observed data by fitting a plane polynomial surface to the data. The study area does not have complex geology and it has spatial extent, therefore, it seemed adequate and reasonable to assume that the regional field is a first-degree polynomial surface (plane trend). All the regional fields were, therefore, evaluated as a two-dimensional first-degree polynomial surface. The expression for the regional field of the study area is therefore, calculated and given as (Nwankwo, 2006):

$$g(x, y) = 7836.3 + 0.0241x + 0.0872y \tag{6}$$

Residual data were then obtained as the deviations from the total intensity data from the fitted plane surface. Upward continuation technique was also utilized to suppress short wavelength components of the residual magnetic anomalies in the study area. The continuation was carried out at a height of 0.282 km.

The study area was divided into eighty-one overlapped blocks for the purpose of spectral analysis as shown in Fig. 2. Each block covers a square area of 45 by 45 km, which represents a square grid of 16 by 16 upward-continued residual field points. These were cosine-tapered before spectral evaluation for heat flow assessments were carried out. Graphs of the logarithms of the spectral energies against frequencies obtained for various blocks were obtained. Linear segments from the low frequency 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 Eq. 2 was used to calculate the depth to causative bodies. Equation 3 was subsequently used to calculate the thickness and hence, the curie-point depths (Nwankwo *et al.*, 2008, 2009 may be checked for details). The Fourier's law Eq. 4 was eventually used to calculate the heat flow by means of Eq. 5.

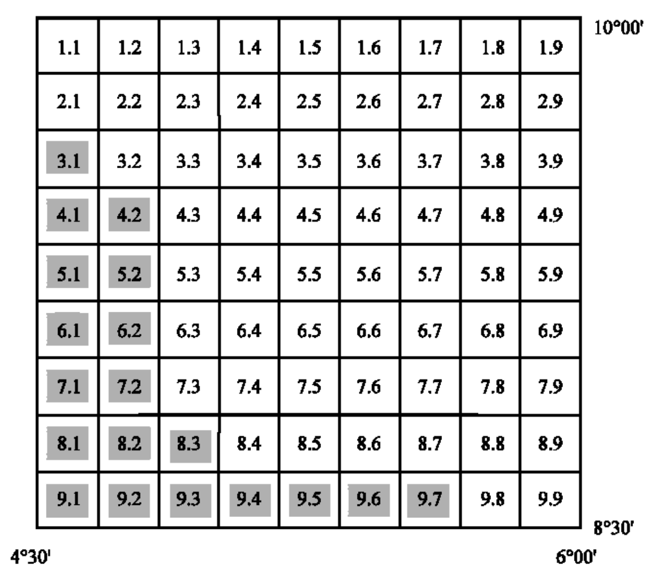

Fig. 2: Diagram showing overlapped blocks of the study area used for spectral analysis. Gray numbered blocks do not have data

RESULTS AND DISCUSSION

Graphs of the logarithms of the spectral energies against frequencies obtained for the various blocks were obtained. Some of the graphs with spectral peak are shown in Fig. 3a-f. The occurrence of a significant peak in the spectrum indicates that the Curie-depths, which define the source

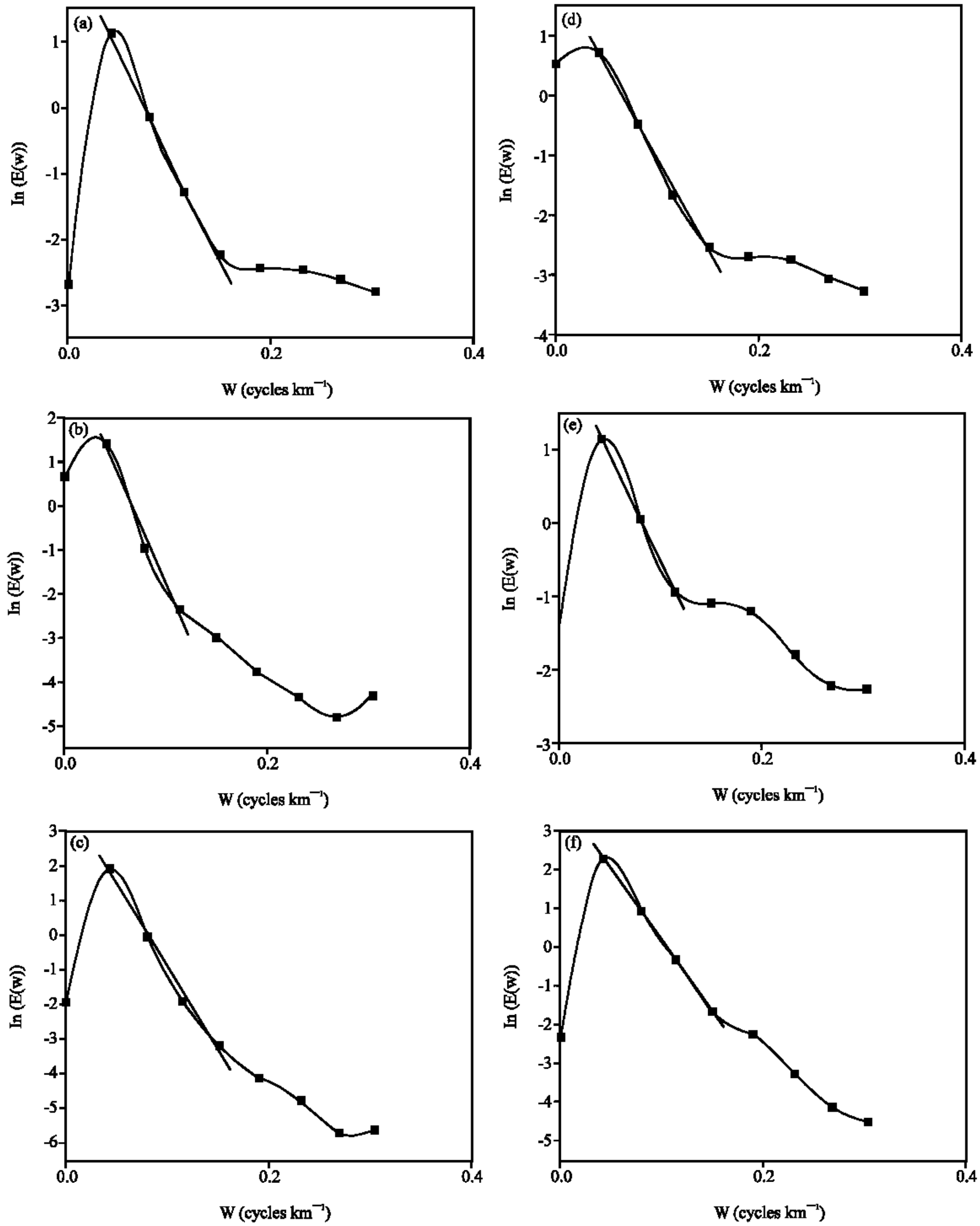

Fig. 3: Power spectra for depth estimations of some of the blocks, (a) block 4.6, (b) block 4.7, (c) block 4.8, (d) block 5.5, (e) block 6.4 and (f) block 6.8

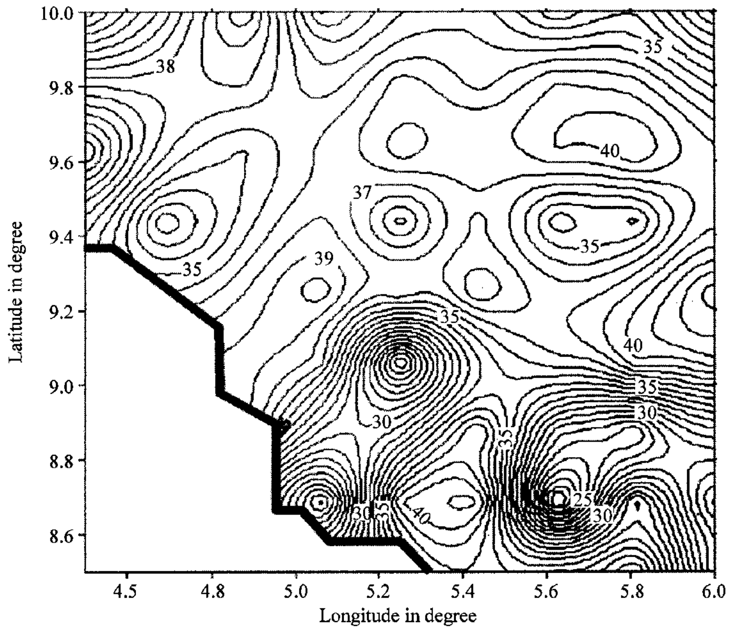

Fig. 4: Geothermal Gradient map of the study area. Contour interval is 1.0°C km^{-1}

bottoms, are detectable. Two linear segments could be drawn from each graph. However, the gradients of the low frequency linear segment were evaluated and the Eq. 2 was used to calculate the depths to top of the causative bodies (deep sources) while Eq. 3 was used to calculate the thickness and hence the curie-point depths. The deeper sources depth has previously been estimated and found to vary from a thickness of 0.52 to 4.38 km (Nwankwo *et al.*, 2008) while the Curie-point depth varies from a thickness of 12 to 30 km (Nwankwo *et al.*, 2009). Using a Curie-point temperature of 580°C and the derived curie-point depths (Nwankwo *et al.*, 2009), geothermal gradient variations in the area were obtained and shown in Fig. 4. Furthermore, thermal conductivity of 2.5 Wm^{-1} $°C^{-1}$ (Stacey, 1977) was subsequently used to estimate the corresponding heat flow anomalies in the study area. The heat flow is shown in Fig. 5.

The result show that the geothermal gradient varies between 19 and 46°C km^{-1} while the ensuing heat flow varies between 30 and 120 mW m^{-2}. Figure 5 shows that in the southeast and southwest of the study area heat flows were found to be less than 60 mW m^{-2} while flows more than 100 mW m^{-2} are found in the northeastern and northwestern parts. All the current literature states that the Curie point depth and of course heat flows are greatly dependent upon geological conditions. Heat flow is the primary observable parameter in geothermal exploration. Generally, the units that comprise high heat flow values correspond to volcanic and metamorphic regions since these two units have high heat conductivities. Additionally, tectonically active regions affect heat flows significantly (Tanaka *et al.*, 1999). The average heat flow in thermally normal continental regions is reported to be above 60 mW m^{-2}. Values in excess of about 80-100 mW m^{-2} indicate anomalous geothermal conditions (Jessop *et al.*, 1976). Anomalous high heat flow values (above 100 mW m^{-2}) have been observed in the study area.

The study area has in the past received limited attention from Earth Scientists partly due to lack of immediate geologic and economic values however, in view of increased efforts to explore for new and more energy locations in Nigeria it is fast becoming an important study area. Since,

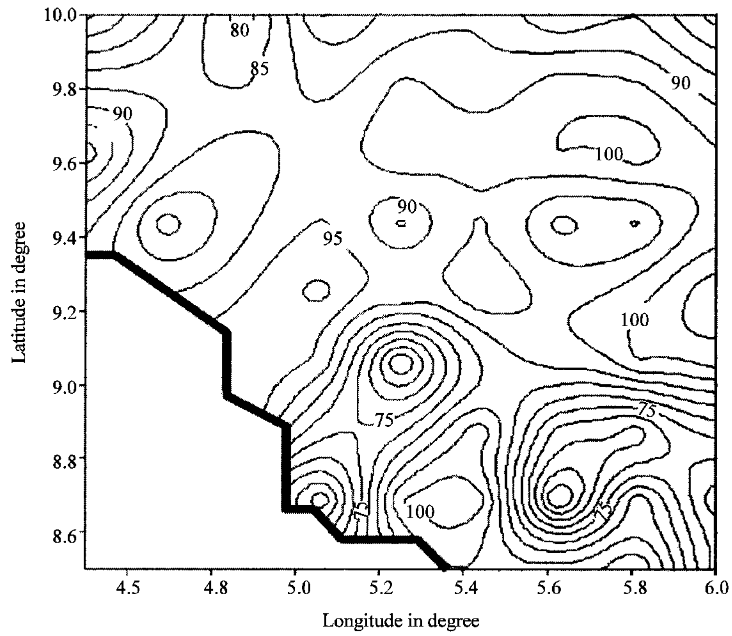

Fig. 5: Heat Flow map of the study area. Contour interval is 5 mW m^{-2}

geophysical studies in the basin are minimal and with no record of crustal temperature studies, the result from this studies would definitely act as an added data. Therefore, heat flow assessment of the area would significantly, compliment the geophysical information of the adjoining basins to the gap of missing crustal temperature information of the central part of Nigeria. This not withstanding, the study has shown that a possibility of geothermal resource exist in Nupe Basin, Nigeria. Therefore, the anomalous heat flow areas observed in this study maybe recommended for further investigation.

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