Bayero Journal of Physics and Mathematical Sciences / Vol. 16, No. 1 / March, 2025. ISSN: 1597 – 9342, Online ISSN: 2795 - 3866

BAJOPMAS JOURNAL 16(1): 8 – 19
Printed in Bayero University, Kano - Nigeria.

DETERMINATION OF GEOTHERMAL POTENTIAL OF LAMURDE HOTSPRING ADAMAWA STATE USING AEROMAGNETIC AND SATELITE-GRAVITY DATA

[1]Ali, A. I. and [2]Kwaya, M. Y.
Department of Physics, Bayero University Kano
Department of Geology, Bayero University Kano
alialiyuidris@gmail.com

Abstract
Some Geothermal parameters of Lamurde and environs are determined by integrating spectral analysis, Euler deconvolution and Source parameter images. High resolution aeromagnetic and satellite gravity are analyzed using the integrated techniques. The spectral analysis revealed the curie point depth (CPD) ranged of 7.21km to 11.74km with an average of 8.92km, the heat flow varied from 123.51mWm^2 to 201.00 $\mathrm{mWm}^2$and the geothermal gradient that ranges between 49.40$°\mathrm{C/km}$ to 73.44$°\mathrm{C/km}$. The average geothermal gradient of 65.96$°\mathrm{C/km}$ is far greater than accepted standard value for geothermal potentiality. The depth to magnetic source as determined by source parameter imaging, ranged from 142.69km to 32329.50km while the bouguer anomaly depth ranges between 94.29km to 2033.34km. Geologically, the structural index of zero ranges between -366.16m for outcropping magnetic anomalies bodies to 3563.80m deep lying magnetic bodies and -691.47m bouguer anomalies (shallow bodies) to3851.69m bouguer anomalies (deep lying bodies) as obtained from standard Euler depths deconvolution. These characteristics revealed from integrating above methods in these study areas and the location of Lamurde hot springs are indication that there might be good sources of geothermal energy for exploration and exploitation.

Keywords: Aeromgnetic Euler deconvolution, Geothermal energy, Lamurde hot springs, Satelite gravity Source Parameter Images.

1.0 Introduction

Geothermal energy is a renewable energy source that is sustainable and reliable which can be used in space heating or cooling, industrial application and most importantly in electricity production. Understanding geothermal starts with understanding the source of this heat which is earth internal heat. This heat energy mostly is manifested on the earth surface in form of volcanoes and fumaroles, hot or warm springs, geysers, streaming grounds and altered grounds,[13]. The most obvious geothermal resources occur when the fluids arise from subsurface to the ground through faulted permeable rock pore. The classification of warm or hot springs are by the fluids temperature that reaches the surface area. The warm spring normally holds a temperature less than 50°C while hot spring holds a temperature greater than 50°C, the spring indicates that dominating fluids inside the geothermal reservoir is steam or hot water dominates [4].

Energy plays a vital role in economic growth, progress and development, poverty eradication and security of any country. Uninterrupted energy supply is a vital issue for all countries today and future economic growth depends critically on the long-term availability of energy from sources that are affordable, reliable and environmentally friendly. The idea of using renewable energy in Nigeria should be greatly encouraged, since the population of the country is 180 million as of 2014 but only 40% has access to electricity [22]. That is to show that energy equity in the country is drastically poor and this can lead to poor industrial growth and high unemployment rate in the country.

In geothermal environment, due to high temperature, the magnetic susceptibility decreases, when magnetic method is used with gravity method, this method can be used to infer heat sources as seen from geothermal exploration in Olkaria [10]. According to [18], due to the fault juxtaposing rocks of differing densities, the gravity method is an excellent exploration choice for identifying the structural setting of the geothermal areas. Since the point of interest in magnetic and gravity measurement are magnetic susceptibility and rocks density, the combined two methods will serve as the efficient methods that can provide detail information about the structural setting of the geothermal reservoir and the heat, since with only magnetic prospect it will be difficult to determine rock fault on the basis of estimated susceptibility

The present proposed case study, Ruwan Zafi hot spring (54°C), is spotted in north of Benue Trough inside a tremendous tectonic structure lamurde anticline, close to Numan in Adamawa State [5]. The water of the spring is warmed by geothermal angle on its path from obscure profundities, in unconfined sandstone aquifer [14]. Hot or warm spring is among several parameters to be considered for an optimum occurrence of geothermal resources, Other parameters are shallow curie point depths, high temperature gradients, high heat production, low regional gravity anomalies, the presence of structural lineaments, the outcropping of younger volcanic or granitic rocks. [13]. Previous researches conducted over Ruwan Zafi hot spring include; determination of curie point depth, heat flow and geothermal gradient using aeromagnetic data. The result revealed a shallow curies point depth and corresponding high heat flow that suggested anomalous geothermal condition [6]. The spectral analysis of aeromagnetic data was also conducted that examined the structure overlaying the area geared toward assessing their geothermal viability [15]. A study conducted by multi-criteria evaluation methods in Northeastern Nigeria revealed that Ruwan Zafi hot spring as the most geothermal surface manifestation [24].

Most parts of Nigeria indicate significant geothermal potentials especially within the Benue trough, the Nigerian sector of Chad basin and the Niger Delta [19]. Many geothermal research has started since the last three decades toward the determination and exploitation of geothermal potentials from Southern region, central region and Northern sedimentary regions, Verheijen and Ajakaiye (1979) estimated heat flow of the center of Ririwai ring complex and the result obtained was almost equal to the world average as they got $38.5\pm1.7 mW/m^2$ [9]. The subsurface temperature distribution in the southern sedimentary province of Nigeria was studied 35 years ago, Corrected bottom hole temperature (BHT) data measurement was used in the oil exploration in the Niger Delta and Anambra basins [9]. According to [8], geothermal studies in Nigeria can be discussed by following the geothermal features (subsurface temperatures and geothermal gradients) of sedimentary province, or by the geothermal springs as geothermal subsurface manifestations. According to [9], the more detailed investigation on thermal springs should explain the origin of heat carried by the water to the surface and the depth of water circulation. This will give an idea and contribute to the possibilities of use of geothermal heat from the sedimentary and Precambrian province in Nigeria.

1.1 Location and Geology of the Study Area

The area is bounded by longitude 11°0'E and 11°0'E, and latitude 12°0'N and 12°0'N located within northern Benue Trough in the Northern Eastern part of Nigeria. The study area falls within the contact between the Northern Benue trough and Northern Eastern Basement Massif, it is located in Gongola Basin. Sedimentation in the Gongola basin began with the deposition of continental Bima Sandstone in the late Aptian – Early Abian [1], which unconformable overlies the granitic Basement complex and consists of feldspathic sandstones and clays which pass upwards into coarse to medium grained sandstones [3].

The study area was underlays by the crystalline basement rocks, younger granites, sedimentary rocks and volcanic rocks [16][2]&[17]. Crystalline basement rocks of the northern and eastern basement complex underlie the northern and southern-eastern parts of the area respectively. The Middle Benue Trough links the upper and lower arms of the Benue Trough sedimentary basin in Nigeria, which is part of the long stretch arm of the central African rift system and one of the seven inland sedimentary basins Nigeria, originating from the early cretaceous rifting of the central west African basement uplift. [17] &[17]. According to [17], the Benue trough is a linear Northeast-Southwest (NE-SW) trending structure characterized by the presence of thick sedimentary cover of varied composition whose ages range from Albian to Maastrichtian.

Geologically, Nigeria consist of crystalline basement and sedimentary basins of different ages. [8]. According to [24], the geologic structures/settings of any area influences it general distribution of its natural resources including geothermal in the upper crust. Records of geothermal potentials manifestations in Nigeria were documented especially within the Benue Trough, Niger delta and Nigerian sector of the Chad basin. [19]. Expressions of subsurface manifestations such as the hot springs, volcanic and lava flow has been documented largely in the Benue Trough and Precambrian basement. There are eight hot springs within the Benue Trough that occur mainly within the middle and upper part of the Trough, the warmest springs are; Akiri (Benue state) and Ruwan Zafi (Adamawa state) having temperature of 54℃ and suggests the occurrence of some geothermal anomalies. [9]. In this study, the hot spring that manifested in Ruwan Zafi area of Lamurde local government of Adamawa state serve as indication for geothermal energy potential found in the Northern part of Benue Trough. The figure (1) is the map of study showing main road and river within the study area.

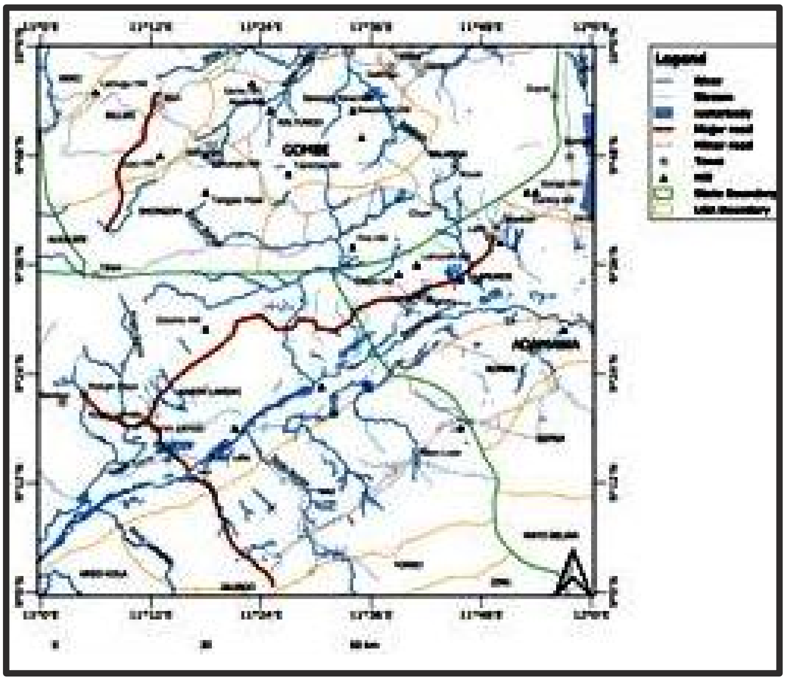


Fig. 1 Geological Map of the study area.

2.1Materials and Methods

The description of methods used material and how data were analyzed and interpreted are discussed below in details.

The high resolution satellite Gravity and Aeromagnetic data were obtained from Nigerian Geological Survey Agency (NGSA). The data were collected along a series of NW-SE flight lines at 80m spacing, 20Km tie lines spacing and at 100m terrain clearance. [24]. The parameters measured were magnetic intensity and gravity anomaly, all necessary corrections were made and the data is of higher resolution.

Gridding of the potential field dataset is the first step in the data analysis to convert it to an evenly spaced two dimensional (2D) grid. To harmonize the aeromagnetic data sheets into a single grid the obtained grids were all digitized and saved to XYZ Geosoft data base format using the utilities tool of the Grid and Image tools on Oasis montaj software after which the data sets were merged to a single data base using the utilities tool of the database tools of the same software. The XYZ Geosoft data format of magnetic and Bouguer anomaly were gridded using the minimum curvature of the grid and image tool of the Oasis Montaj software to produce the total magnetic intensity (TMI) map and Bouguer gravity map of the study area in a grid size of 200 to avoid over or under sampling based on the sampling distance of the two dataset. as shown in figures (3.1 & 3.2) below:

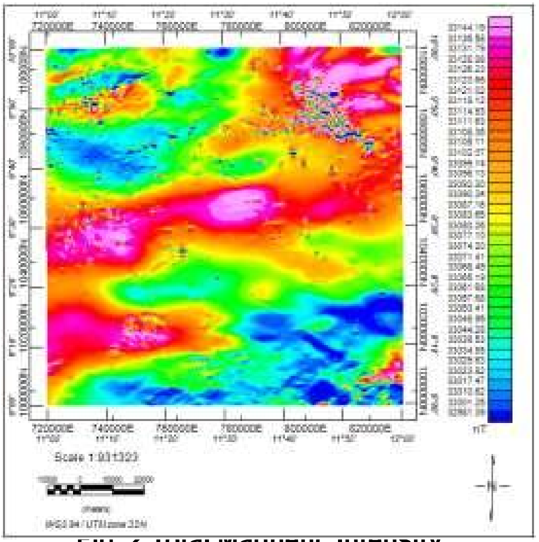


Fig. 2 Total Magnetic Intensity Map of study area.

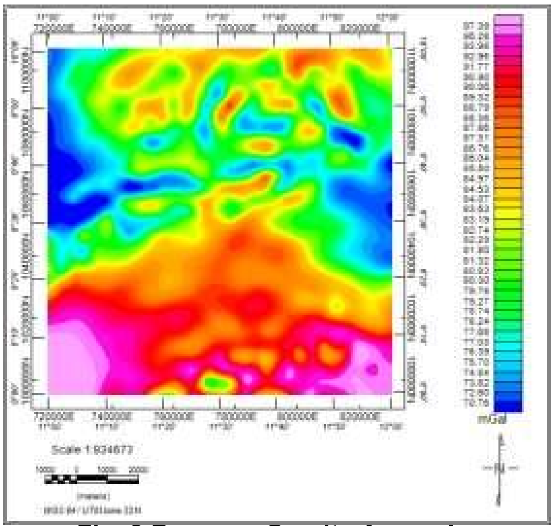


Fig. 3 Bouguer Gravity Anomaly Map of the study area.

2.2 Spectral Analysis

Spectral analysis was used to estimate the depth to magnetic sources, the Curie point depth and determined geothermal gradient as well as the heat flow in the area. It is often applied using the azimuthally aver- aged power spectrum of magnetic anomalies [21]. The power spectra of the magnetic anomaly are expressed by [21]

$$\phi_{\Delta T} = \emptyset_m(k_x, k_y).F(k_x, k_y) \quad (1)$$

where $\emptyset_{\Delta T}$ and $\emptyset_{\Delta m}$ are the power spectra of the magnetic anomaly and the magnetization, respectively, k_x and k_y, are $\emptyset_{\Delta T}(k_x, k_y)$ wavenumbers in the direction of x and y, respectively, and

$$F(k_x, k_y) = 4\pi^2 C_m^2 |\Theta_m|^2 |\Theta_f|^2 e^{-2kZ_t}(1 - e^{-K(Z_b - Z_t)})^2 \quad (2)$$

where C_m is the constant. Θ_f and Θ_m are the factors related to the geomagnetic field direction and the magnetization direction, correspondingly. Z_t and $Z_b$are the top depth and bottom depth of the magnetic layer, respectively. K = $\sqrt{k_x^2 + k_y^2}$, k_x and k_y are the wavenumbers in the direction of x and y.

Assuming that the magnetization and geomagnetic field directions are constant, Eqn. (2) can be rewritten as

$$\Theta_{\Delta T}\ (k_x, k_y) = A\Theta_M(k_x, k_y)e^{-2kz_t}(1 - e^{-k(z_b - z_t)})^2 \quad (3)$$

where A is a constant.

Using random magnetization models, and if magnetization M(x,y) is completely random, $\Phi_M(k_{y,}k_x)$ will be constant [20]. As a result, Eg. (3) becomes:

$$\ln(\Theta_{\Delta T}\ (k_x, k_y)) = B_1 - 2kz_t \quad (4)$$

where B is constant.

The low wave number portion of the power spectrum can be approximated to estimate the centroid depth (z_o) of the magnetic layer [20]:

$$\ln(\Phi_{\Delta T}(k_x, k_y)^2 k) = B_2 - KZ_o \quad (5)$$

where B_2 is constant. When the top depth (z_t) and the centroid depth (Z_o)of the magnetic layer are gotten from Eq. (4) and (5) respectively, the bottom depth (z_b) can be calculated as;

$$z_b = 2z_o - z_t \quad (6)$$

The heat flow as defined by Fourier's law;

$$Q = d\left[\frac{dT}{dZ}\right] \quad (7)$$

Where Q is the heat flow, d is the coefficient of thermal conductivity and $\frac{dT}{dZ}$ is the temperature gradient that is assumed to be constant [6].

[12] defined the curies temperature (θ), as:

$$\theta = Z_b\left[\frac{dT}{dZ}\right] \quad (8)$$

Equations (7) and (8) gives a relationship between curie point depth and heat flow which can then be use in the estimation of geothermal gradient:

$$Q = d\left[\frac{\theta}{Zb}\right] \quad (9)$$

$$\left[\frac{dT}{dZ}\right] = \left[\frac{\theta}{Zb}\right] \quad (10)$$

where z_b is the basal depth, z_t top to boundary depth, z_o depth to centroid, Q is the heat flow, θ is the curies temperature and $\frac{dT}{dZ}$ is the temperature gradient. Equation (5) to (6) are going to be used to carry out the calculations of heat flow, curie point depth and geothermal gradient q.

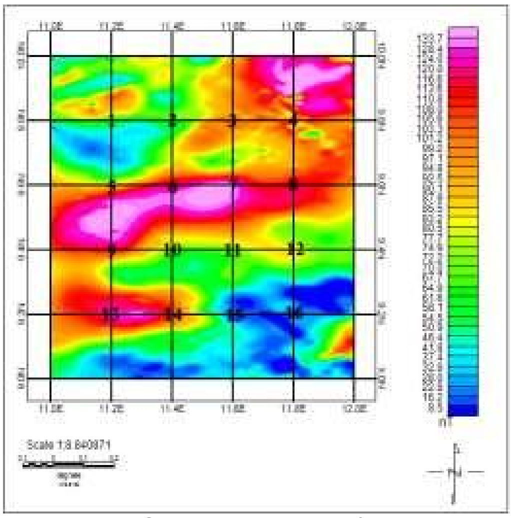
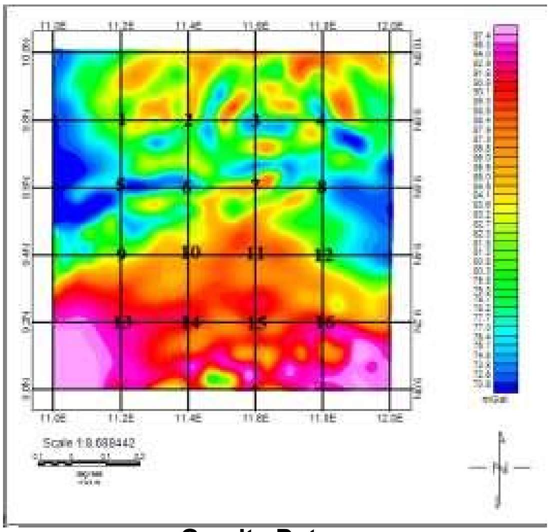


Fig. 4 Spectral blocks of the Aeromagnetic data.



Gravity Data.

2.3 Source Parameter Imaging (SPI)

The source parameter imaging techniques uses the local wave number to estimate the depths to the magnetic or gravity sources that obtained from the analytical signal [*7*]. The function of the SPI is easily, quickly and powerful in calculating the depth of sources for gravity/magnetic fields. The SPI method is based on the extension to estimate magnetic/gravity depths. This was done using the SpI tool which was loaded from the GX Menu of the Oasis Montaj software.

[*11*] defined the analytical signal A(x,y,) as:

$$A(x,y,) = \frac{\partial M(x,y)}{\partial x} - j\frac{\partial M(x,z)}{\partial z} \quad (11)$$

Where M(x,z) is the magnitude of the anomalous total magnetic field, j is the imaginary number, z and x are Cartesian coordinates for the vertical and the horizontal directions respectively.

Both horizontal and vertical derivatives comprise of real and imaginary parts of 2D analytical signal of Hilbert transformation [*11*], given as:

$$\frac{\partial M(x,z)}{\partial x} \Leftrightarrow \frac{\partial y M(x,z)}{\partial z} \quad (12)$$

where ⇔ denotes a transformation pair.

[*22*] define the local wave number k (in radian per ground unit) for this analytical signal to be

$$K = 2\pi f_o \quad (13)$$

where f_o is the cycles unit and K is the wave number in radian per gram unit, the wave number for a contact profile as:

$$K_{max} = \frac{1}{h} \quad (14)$$

where K_{max} , is the wave number of the analytical signal and h, is the depth to the point contact given as:

$$h = \frac{1}{k_{max}} \quad (15)$$

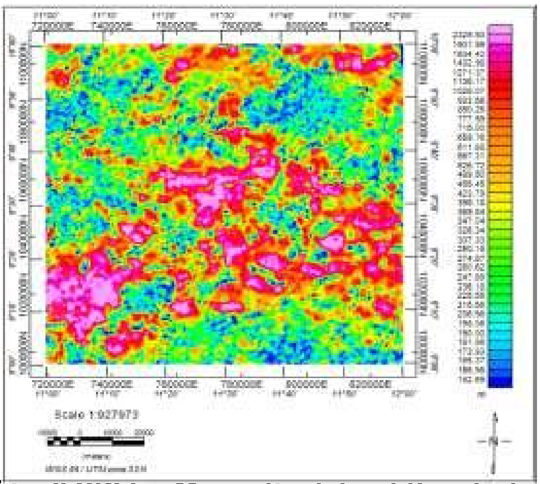


Fig. 6 SPI for Magnetic data of the study area.

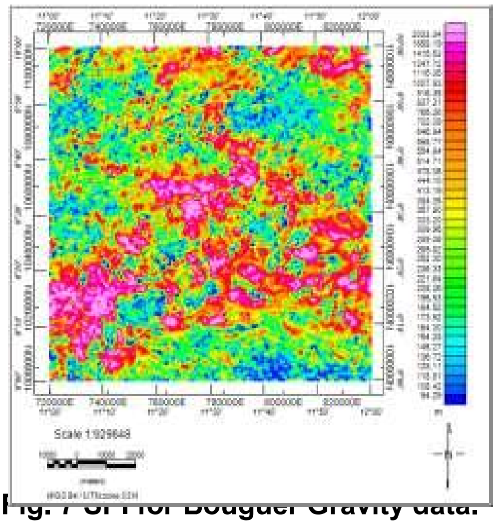


Fig. 7 SPI for Bouguer Gravity data.

2.4 Euler Deconvolution

Maps for Bouguer gravity and aeromagnetic data were respectively created as shown in figures (8) and (9). The depths were estimated using vertical derivatives in three dimensional (3D). vertical derivatives enhance shallow magnetic bodies. As a result of that, a shallow magnetic anomalies depths of different structural indices were displayed by the Euler method. In the Euler depths computation, a 10% depth tolerance was given over a maximum accepted depth of 10km which is half of the average Curie point depth. Different structural index numbers were tried on the aeromagnetic and satellite gravity data but it was found that the index number; 0, 1 and 2 were the best for the data as it reflected the geological information of the area. The pink color indicates shallow magnetic and Bouguer anomaly bodies while the blue indicates deep lying anomalous bodies respectively.

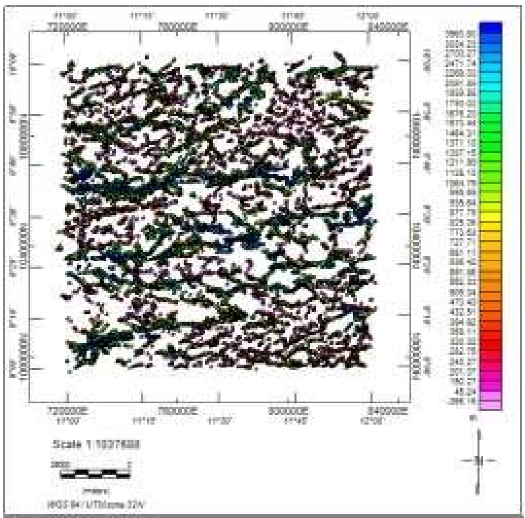
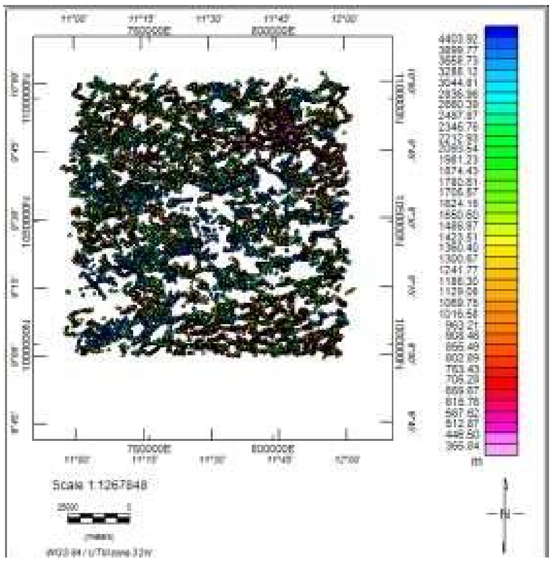


Fig. 8 Euler deconvolution for SI(0)



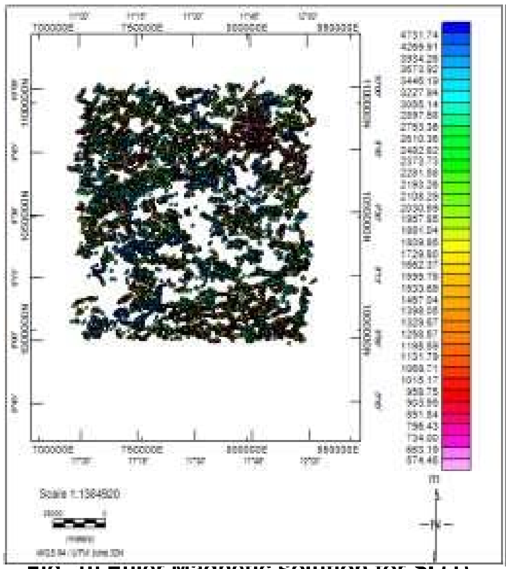


Fig. 10 Euler Magnetic solution for SI (1)

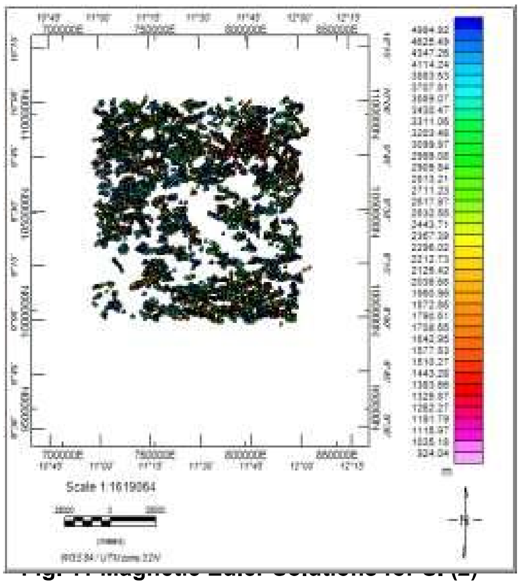


Fig. 11 Magnetic Euler Solutions for SI (2)

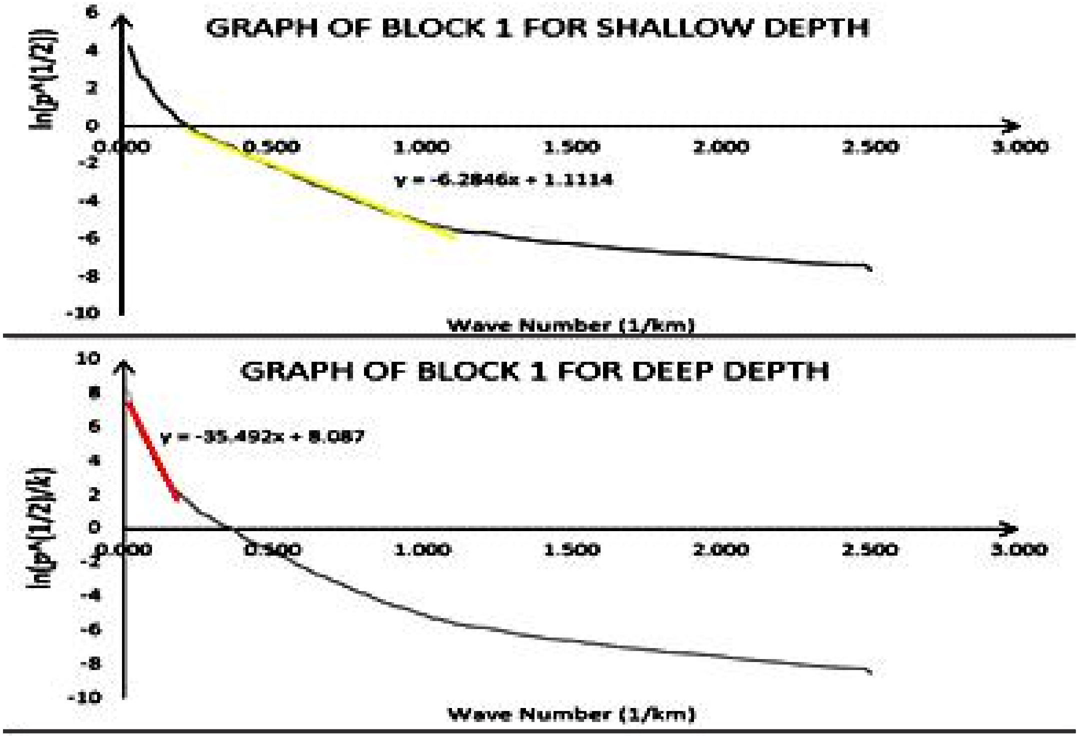


Fig. 12 Graph of depth to Shallow for Block 1.

RESULTS AND DISCUSSIONS

The results and interpretations of the various analyses that were carried out aredisplaed discussed below.

3.1 Spectral analysis Result

Table 1: Result obtained from the spectral analysis of Aeromagnetic data.

Spectral Bock	Latitude	Longitude	Depth to the Top z_t(km)	Depth to the Centre z_o (km)	Depth to Base z_b(km)	Curie Point Depth (km)	Geothermal gradient (°C/km)	Heat flow (mWm^{-2})
1	9.8	11.2	1.000	5.648	8.579	10.30	56.33	140.83
2	9.8	11.4	0.812	6.276	8.470	11.74	49.40	123.51
3	9.8	11.6	0.907	4.422	9.310	7.94	73.07	182.67
4	9.8	11.8	1.014	4.114	8.660	7.21	80.40	201.00
5	9.6	11.2	0.944	4.537	10.014	8.13	71.35	178.37
6	9.6	11.4	0.829	4.930	9.882	9.03	64.23	160.57
7	9.6	11.6	0.931	4.881	9.804	8.83	65.69	164.21
8	9.6	11.8	0.884	4.425	9.621	7.97	72.80	182.01
9	9.4	11.2	0.934	5.234	8.771	9.53	60.84	152.10
10	9.4	11.4	0.885	5.433	8.409	9.98	58.10	145.26
11	9.4	11.6	0.872	4.825	8.636	8.78	66.07	165.18
12	9.4	11.8	0.721	4.732	9.439	8.74	66.35	165.87
13	9.2	11.2	1.038	5.382	8.834	9.73	59.63	149.09
14	9.2	11.4	0.835	4.688	9.209	8.54	67.91	169.77
15	9.2	11.6	0.842	4.577	7.960	8.31	69.78	174.46
16	9.2	11.8	0.571	4.234	9.827	7.90	73.44	183.61
Average			0.876		9.09	8.92	65.96	164.91

Observations from the Table 1 of results above have shown that the calculated depth to top ranged from 7.96km to 9.88km with average depth of 9.09km. The curie point depth (CPD) range from 7.21km to 11.74km with an average of 8.92km which could be as a result of thick sediment and the shallow curie point depth in the area could be an account of the intrusion from the igneous rocks or magmatic materials. The geothermal gradient ranged from 49.40°C/km to 73.44°C/km with average of 65.96°C/km. The heat flow in the area varied between $123.51mWm^{-2}$ to $201.00mWm^{-2}$ with an average of $164.91mWm^{-2}$ heat flow. Observation made from Table 1 above showed that as the curie point depth decreases, the heat flow increases and vice versa. This is in good agreement with the findings [*6*], [*15*] & [*24*]. [*6*] estimated the heat flow that ranges from 150.73 to $132.73mWm^{-2}$ with average of $139.12mWm^{-2}$, and the geothermal gradient that varies between 12.16 and 15.67°C/km with the average of 13.39°C/km, wich shows similar trends using aeromagnetic data. [*15*], assessed the geothermal potential of Ruwan Zafi which is part of the study area. The results obtained from the geothermal gradient varied between 33.79 and 69.01°C/km and the corresponding heat flow ranges from 120.26 to $172.52mWm^{-2}$ the shows similar fluctuation, they used high resolution airborne magnetic data. [*24*], used integrated multi criteria methods to study the factors that influencing geothermal energy prospects around Northeastern Nigeria. The result obtained revealed that Ruwan Zafi Hot spring area as one of the areas with very high geothermal potentials.

3.2 Euler Deconvolution Result

Table 2. Results of Euler Deconvolution from Aeromagnetic and Satelite gravity.

Structural Index(SI)	Depth Ranges(m)	Depth Range (m)
	Aeromagnetic Data	Bouguer Gravity Data
0.0	3563.80 to 366.16	–691.47 to 3851.69
0.5	365.84 to 4403.92	1325.48 to 5130.71
1.0	574.46 to 4731	1839.36 to 5350.66
2.0	924.04 to 4944.92	2629.79 to 5575.75

The Euler-3D solutions (table 2) show that the depth ranges for the TMI field data are between 3563.80m to -366.16m for SI of zero, -365.84m to -44403.92m for SI of zero point five, 574.46 to -4731m for index one and 924.04m to to -4944.92m for SI of two. While Bouguer gravity result shows that the depths range is between -691.47m to -3851.69m for SI of zero, 325.48 to -5130.71for SI of zero point five, 1839.36m to 5350.66m for SI one, and 2629.79m to -5575.75m for the SI two, the Euler-3D solutions show that the depth ranges for the TMI field data are between 3563.80m to -366.16m for SI of zero, -365.84m to -44403.92m for SI of zero point five, 574.46 to -4731m for index one and 924.04m to to -4944.92m for SI of two. While Bouguer gravity result shows that the depths range is between -691.47m to -3851.69m for SI of zero, 325.48 to -5130.71for SI of zero point five, 1839.36m to 5350.66m for SI one, and 2629.79m to -5575.75m for the SI two.

3.2.1 Depth Estimation

The Euler depth solutions identified the depth extent of faults and fractures were estimated for gravity (SI 1 & 2) and magnetic (SI 1 & 2) which were plotted on the residual gravity RTE and magnetic anomaly maps (Fig. 8 to Fig. 11), respectively. The depth solution for more than 1000m were observed to be concentrated along SW-SE trending low zone in residual gravity and RTE magnetic maps. This indicates that SW-SE trending low anomaly zone related to the regional fault. The variation of depth solutions from 1800 to 5000 m in both gravity and magnetic data may be related to the depth extent of the shallow faults and fractures beneath the sediments.

3.3 Source Parameter Images

Table 3. result of Source Parameter Images

Aeromagnetic data	Bouguer Gravity Data
142.69 to 2329.50	94.29 to 2033.34

Table 3.3, shows the depths to magnetic and gravity sources. The estimated depths to the magnetic sources from SPI ranges from142.69m to 2329.50m and basement depth obtained from SPI ranges from 94.29m to 2033.34m. The highest depth of magnetic source can be found at the southeastern and southwestern parts of the study area (Fig. 6), while highest depth of baouguer gravity (shallowest) is at southeastern and southwestern parts of the study area respectively (fig.7). The depth to the shallow sources of magnetic and gravity figures (3.21 & 3.22) ranges between 94.29m and 142.69m, while depth to deeper sources varied from 2.3295km to 2.03334km. these results are in consistent with the results obtained by spectral analysis. [7], Suggested that, these deeper sources are caused by crater lakes which might have influenced due to deep weathering. The shallow sources show the existence of younger granites and series of volcanic plugs which are responsible for the deeper sources with thick sedimentary covers

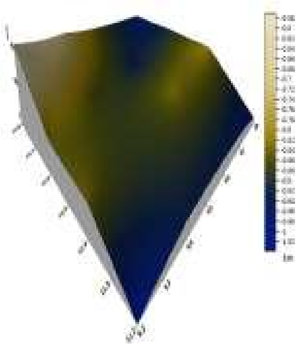


Fig. 13. 3D Map of Depth to the Magnetic Sources

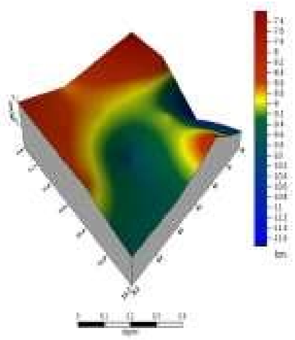


Fig.14. 3D Map Depth to basement of magnetic sources.

4. Conclusion

The interpretation of geothermal parameters of Lamurde and environs Adamawa state, Nigeria was conducted using aeromagnetic and satellite gravity data in order to determine the geothermal energy potential of the area. The analysis revealed that the area is characterized by high heat flow and shallow curie point depth.

The result of the depth to basement in the study area agrees with the work of previous research works in the Northeastern Benue Trough. The deeper depth can be found in latitude 9°.2'N, 9°.8'N and 9°.8'N, and longitude 11°.2',11°.8E and 11°.2E respectively. While the lower depth around latitude 9°.4'N and 9°.2'N, and longitude 11°.8'E and 11°.8'E. the areas of low curie point depth correspond to high geothermal gradient. Based on these results from the lo values of curie point depth in some areas, there is possibility that the study area has geothermal potentials. The high geothermal heat flow values ranges from 183.61mW/m^2 to 201.00mW/m^2 with average of 164.91mW/m^2 is more than the accepted standard value for geothermal heat flow potentiality, therefore this area is potentially active of geothermal and can be used for geothermal production. This study shows that the energy potential deduced from both active potential fields (natural force fields) correlate one another in assessing geothermal potential of the study area.

REFERENCE

[1] Abubakar, M.B., Obaje, N.G., Luterbacher, H.P., Dike, E.F.C., & Ashraf A.R., (2006) A Report on the occurrence of Albian-Cenamonian elater-bearing pollen in Nasara-1 well, upper Benue Trough, Nigeria; Biostrsatigraphic and Palaeoclimatological implications. Journal of African Earth Sciences, 45(3), 347-354

[2] Ajayi, C.O. and Ajakaiye, D.E., 1981. The Origin and Peculiarities of the Benue Trough, another look from the recent gravity data in the Middle Benue, *Tectonophysics*, vol. 80, pp. 285-303.

[3] Guiraund, M. (1990). Tectono-Sedimentary framework of the early Cretaceous Continental Bima formation (Upper Benue Trough, NE Nigeria). Journal of African Earth Sciences, 10(1-2), 341-353

[4] Halim, R. A. (2018). Geothermal Potency and Development Master Thesis. *MSc in environmental and Energy Management University of Twente*

[5] Ikeagwuani, I.O., D.C. Olusola., (2015). Exploration and Application of geothermal energy in Nigeria. *International journal of scientific and engineering Research, Vol.6 Issue 2, Pg 728. ISSN 2229-5518*

[6] Kasidi, S. (2019), Determination of curies point depth, heat flow and geothermal gradient from high resolution Aeromagnetic Data around Lamurde Area, Adamawa state, North eastern Nigeria. *Open journal of geology, 9,829 – 838*

[7] Kasidi, S., Alkali, S.C., and Yusuf S.N. (2016), Source Parameter Imaging (Spl) Interpretation of Aeromagnetic Data over the Young Granite Rocks around Amper and Environs, North Central Nigeria. *ADSUJR 04(2): AUGUST,2016*

[8] Kurowska, E. and Schoeneich, K. (2010). Geothermal exploration in Nigeria. *Proceeding world geothermal congress 2010*

[9] Kwaya, M.Y., and Kuroskwa, E. (2018). Geothermal exploration in Nigeria, Country update. *Proceeding 7th African Rift Geothermal conference Kigali 2018.* Pg *3*

[10] Mariita, N.O. (2013) The strength and Weakness of Gravity and Maggnetic methods as Exploration tools geothermal energy. *Kenya Electricity Generation Company KenGen United Nations University, Geothermal Training Program*

[11] Nabighian, M. N. (1972). The Analytic Signal of two dimensional magnetic bodies with polygonal cross section: Its properties and use for automated anomaly interpretation. Geopgysics. 37(2). pp. 507-517

[12] Nwankwo ,C., & Ekine, A. (2010). Geothermal gradients in the Chad Basin, Nigerian, from botton hole temperature logs. International journal of Physics sciences, 4(12), 777-783.

[13] Ochieng , L. O. (2013). Overview of Geothermal Surface Exploration Methods. Presented *at a short course VIII on Exploration for Geothermal Resources, Organized by UNU-GTP.GDC and Ken Gen at lake Naivasha, Kenya*

[14] Omosule, S.S., and Joshua. E.O., (2013). Evaluation of the existing *state of geothermal exploration and development in* Nigeria*. journal of Advances, physics journal of advances in physics*

[15] Onyejiuwaka, I.S., and Iduma, U.K. (2020) Assessment of geothermal energy potential of Ruwan Zafi, Adamawa state and Environs, Northeastern Nigeria, using high Resolution Airborne magnetic Data.

[16] Offodile, M.E., 1976. The geology of the middle Benue Trough, Nigeria, Special volume of Paleontological Institute, University of Uppsala, vol. 4, pp.1-66.

[17] Obaje, N.G., 2009. Geology and Mineral Resources of Nigeria, Lecture Notes in Earth Sciences, Springer, Berlin Heidelberg.

[18] Santos, P.A., and Rivas, J. (2015). Gravity surveys contribution to Geothermal exploration in EL SALVADOR: A case of Berlin, Ahuachapan and San vicente areas. *Geothermal area LaGeo S.A. de C.V. Santos Techla, La Libertad. EL SALVADOR, C.A. United Nations University Geothermal Training Program.*

[19] Shirputda, J.J. (2019). Assessment of geothermal Resources in the Nigerian sector of the Chad Basin, North-East Nigeria. *National center for petroleum researchand development- NCPRD. Energy commission of Nigeria. Abubakar Tafawa University Bauchi. GTP, United Nations University. Pg 2, Report 620.*

[20] Tanaka, A., Okubo, Y., Matsubayashi, O., 1999. Curie point depth based on spectrum analysis of the magnetic anomaly data in East and Southeast Asia. Tectonophysics 306 (3), 461–470. https://doi.org/10.1016/S0040 -1951(99)00072-4.

[21] Tanaka, A., 2017. Global centroid distribution of magnetized layer from world digital magnetic anomaly map. Tectonics 36, 3248–3253. https://doi.org/ 10.1002/2017T C004770.

Thurston, J. B. and Smith, R. S. (1997). Automatic conversion of magnetic data to depth, dip and susceptibility contrast using the SPI^{TM} method. Geophysics, 62, pp, 807-813

[22] World Energy Council, (2014). World Energy resources: Geothermal. hhtp//www.worldeneregy.org

[23] Yusuf, A., San, L.H., and Sabir, I.A. (2021). A Preliminary geothermal prospectivity mapping based on intergrated GIS, Remote sensing and geophysical techniques around Northern-Eastern Nigeria. *Sustainability 2021,13,8525 https//doi.org/10.3390/sa13158525*

[24] Zira, A.M., 2013. Challenges and prospects of geophysical exploration of geothermal system for National Development, Academic Journal of Interdisciplinary Studies, MCSER Publishing, Rome, Italy, vol. 2, No. 12, pp. 137-143.