Journal of the Nigerian Association of Mathematical Physics
***Volume 60* (April – June *2021 Issue*), pp149 –156**
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HEAT FLOW AND GEOTHERMAL GRADIENT STUDIES IN PARTS OF SOUTHERN BENUE TROUGH

Nwokoma E.U.[1*], Ijeh B. I.[1], Azunna D. E[2] and Anyadiegwu F.C[1].

[1]Department of Physics, Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria
[2]Department of Physics, Clifford University, Owerrinta, Abia State, Nigeria

Abstract

Geothermal and heat flow studies were carried out in parts of Southern Benue Trough covering Abia, Imo, Enugu, Anambra, Ebonyi, Cross River, and Benue States. The study area lies between latitudes 05° 00′ N and 07° 00′ N and longitudes 07° 30′ E and 09° 00′ E. Nine airborne magnetic data sheets of Nsukka, Igunmale, Ejekwe, Udi, Nkalagu, Abakaliki, Okigwe, Afikpo and Ugep with sheet numbers 287, 288, 289, 301, 302, 303, 312, 313, 314 respectively were merged into one composite sheet and was later divided into 36 spectral blocks for consideration. Spectral analysis was conducted on each of the spectral block to obtain the Curie Point Depth, geothermal gradient and the heat flow. The Curie point depth ranges from 5.6-13.7 km with an average of 8.8 km. The Geothermal gradient ranges from 41.5 to 101.7^{0}C/km with an average of 66.9 ^{0}C/km while the heat flow ranges from 103.5 to 254.4 mW /m^2 with an average of 167.5 mW /m^2. It was observed that Igunmale, Ejekwe, Oju, Ogoja and Oturkpo have higher geothermal prospects with volcanic activities than Ideato, Orumba, Uzo-Uwani, Arochukwu and Ikom and the variations in the heat flow indicate a random distribution of magma conduits

Keywords: Geothermal Gradient, Heat flow, Curie Point.

INTRODUCTION

The transfer of heat or thermal energy to the earth's surface is known as heat flow (SMU, 2021)[1]. The source of the heat from the earth’s interior comes mostly through the cooling of the earth's center and generation of radioactive elements like thorium (Th), Uranium (U) and/or potassium (K). Heat produced through the process of radioactive decay of U^{235},U^{238}, Th^{232} and K^{40} constitute 80% of the heat in the earth’s interior while 20% of it comes from a mix of planetary accretion heat and residual heat (Sanders, 2010; Arndt, 2011)[2,3]. Heat moves from the deep hot region to the surface because the earth’s interior is much hotter than the surface. Heat flow anomalies exist in various sections of the world, areas with high radioactivity or thin crust usually have high rate of heat flow. However, There are several places that have higher heat flow anomalies above the average crustal flow of heat without a well-defined radioactive or tectonic explanation (SMU, 2021).[1]

Heat transfer occurs majorly in three ways; conduction, convection and radiation. Whereas thermal conduction involves the transfer of energy through matter, convection involves the energy carried with moving matter and radiation involves energy carried by electromagnetic waves especially when matter is absent (Cermark *et al., 1991)*[4]. For the subsurface, heat transfer is majorly through conduction and convection which is the usual mechanism for heat transfer. Figure 1 shows the heat transfer mechanisms within the earth.

Corresponding Author**:** Nwokoma E.U., Email: nwokoma.esomchi@mouau.edu.ng, Tel: +2347039846930

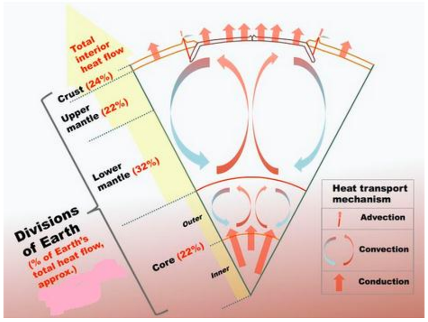

Fig 1: Heat transfer mechanisms within the Earth, along with the percentage amount of heat flow in each layer (Doney *et al.*, 2019)[5].

Heat constantly flows from its sources within the surface of the earth and there is an estimated mean heat flow of 65mW/m^2 and 101mW/m^2 over the continental and oceanic crusts respectively (Pollack *et al.*, 1993)[6]. Rock cores or cutting on a device that tests the amount of energy a rock sample can pass are used to assess thermal conductivity.
Consider a solid body with a slab of horizontal boundaries $z = z_1$, $z = z_2$ (Figure 2). The heat flux q which is the rate at which energy flow through the area is related to the temperature distribution dT, thickness of the material dz and the thermal properties of the conducting body K.

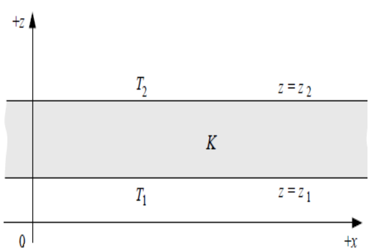

Fig. 2: Heat flux through a slab
The heat flux q measured in Wm^{-2} is as expressed in equation 1 (Aniko and Elemer, 2017)[7];

$$q = -K\frac{dT}{dz} \quad \ldots (1)$$

where K = Thermal conductivity of the material
$dz = z_2 - z_1$
$dT = T_2 - T_1$;
T_1 and T_2 are temperatures at the lower and upper surfaces respectively.
Equation 1 is often called Fourier's law of conduction where *K* which is never negative and it shows how conductive the material is. The higher the conductive nature of the material, the higher the value of *K* measured in Wm^{-1}deg^{-1}. The negative sing on the RHS explains the fact that heat always flows from hot region to cold region. If however the temperatures of the upper and lower surfaces are identical irrespective of their magnitude, then there will be no heat flux on the material. Nevertheless, the heat flux is smaller if the material is thick ($z_2 >> z_1$) than when it is thin. Geothermal gradient γ can be deduced from 1.1 thus

$$\gamma = dT/dz. \quad \ldots (2)$$

Geothermal gradient therefore can be defined as the rate at which temperature increases with increasing depth beneath the earth's surface. The magnitude of the geothermal gradient depends on the rate at which heat is production at depth, the dynamics of the systems in addition to conductivity of rocks (Arndt, 2011)[3]. The geothermal gradient is calculated in ^{0}C/m (or K/km) and it has average values ranging from 0.045 – 0.065 ^{0}C/m on a continental scale (Aniko and Elemer, 2017)[8].
Some of the previous studies on heat flow and geothermal gradient can be seen in the works of Akpabio et al (2003)[9], Akpabio et al (2013)[10], Adedakpo et al (2013)[11], Anomohanam (2013)[12], Odumodu and Mode (2014)[13], Chukwueke et al (1992)[14], Etim et al (1996)[15], Ogagarue (2007)[16] and Brooks et *al* (1999)[17].

The Study Area

The geographical coordinates of the study area lie between latitudes 05° 00′ N and 07° 00′ N and longitudes 07° 30′ E and 09° 00′ E. The Southern Benue Trough includes the southernmost part of the Benue Trough, which makes up the major sedimentary basin in Africa, with a length of over 1000 kilometers and a width of 150 to 250 kilometers. It is a portion of the Cretaceous West African Rift System (WARS), that stretches for about 4000 kilometers from Nigeria to the neighboring Republic of Niger before terminating in Libya. (Binks and Fairhead 1992)[18]. From southwest to northeast, the Benue trough is divided into three geographical and structural regions: the Lower, Middle, and Upper Benue Troughs as shown in figure 3.

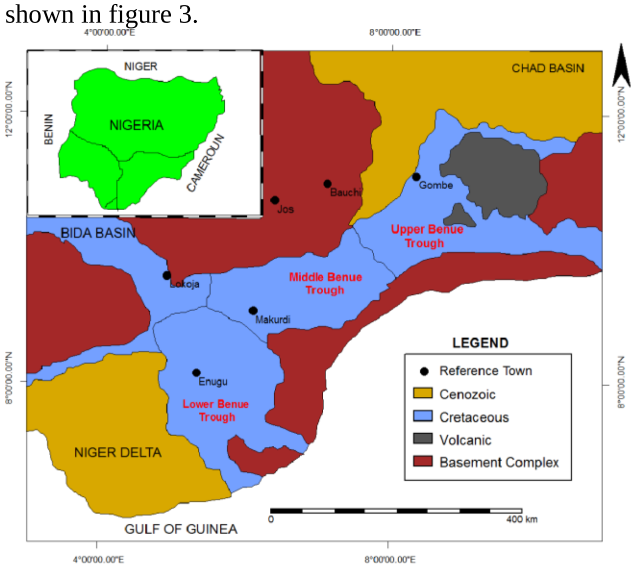

Fig. 3: Map of the Benue Trough of Nigeria modified from Obaje et al (1999)[19]

The states are covers Abia, Imo, Enugu, Anambra, Ebonyi, Cross River, and Benue States, the major towns being Nsukka, Igumale, Ejekwe, Udi, Nkalagu, Abakaliki, Okigwe, Afikpo, and Ugep. The geology of the study area is as shown in figure 4. It comprises of the Ogwshi/Asaba, Ameki/Nanka, Imo, Nsukka, Mamu and the Odukpani formations. They also contain the Asu-River, Eze-Aku, Awgu and Nkporo groups with some basement complex and Ajali sandstone. It contains rocks of cretaceous to tertiary ages with its stratigraphic history characterized by three sedimentary phases namely; the Abakili-Benue Phase, the Anambra-Benin Phase and the Niger-Delta Phase with their ages being Aptian-Satonian, Campanian-Mid Eocene and Late Eocene-Pliocene respectively (Azunna *et al.*, 2021)[20]

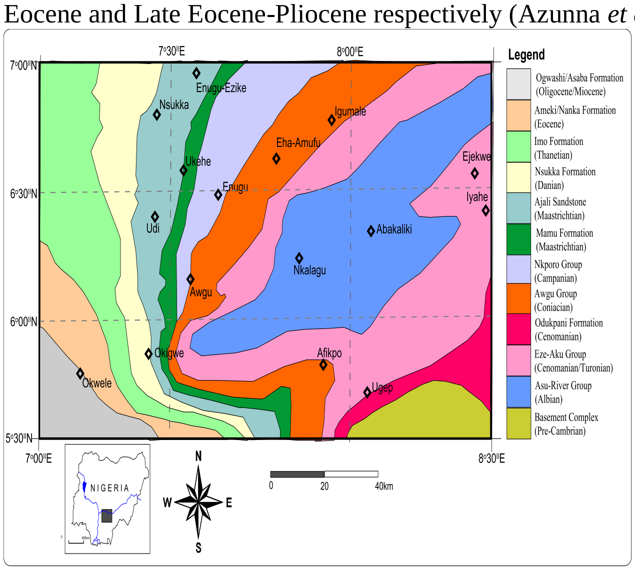

Fig. 4: Geology map of the study area

MATERIALS AND METHOD

The airborne magnetic data of the study area was acquired from the Nigeran geological survey agency (NGSA). On a scale of of 1:100,000 covering Nsukka, Igunmale, Ejekwe, Udi, Nkalagu, Abakaliki, Okigwe, Afikpo and Ugep with sheet numbers 287, 288, 289, 301, 302, 303, 312, 313 and 314 respectively. The Total Magnetic Field Intensity data was acquired using a 3 ScintrexCesium vapour magnetometers mounted in about 7 Cessna Caravan fixed-wing aircrafts. The data recording interval was 0.1s or less than 7m. Projection method used in processing the data was the Universal Transverse Mercator (UTM) and the WGS 84 as Datum. The Spheroid model used was the Clarke 1880 (modified), 33ºE Central Meridian, a scaling factor of 0.9996, a 500,000m X Bias, a 0m Y Bias and 50m grid mesh size were the plotting specification. An IGRF 2005 model was used for the calculation of declination and inclination (NGSA 2010). 500 m line spacing – NW-SE orientation, 25 km control line spacing – NE-SW 80 m mean terrain clearance.

The data sheets were merged into one composite sheet to obtain the total magnetic field intensity TMI of the study area. The Total Magnetic field Intensity value Z was stripped of 33,000 nT by the NGSA after the data was acquired, a series of filtering and reductions are applied to the 2D gridded data in both wave number and Fourier domains in order to get the spectral analysis, heat flow and geothermal gradient. These processes were done using the Geosoft Oasis Montaj software and the other analysis and interpretation software.

The Filtered merged magnetic data over the study area was later divided into 36 spectral blocks as shown in figure 5 with an area of 27.9 km^2, (27.900 m^2) and was subjected to processing to generate as many depth points as possible for a better depth estimation and perfect representation.

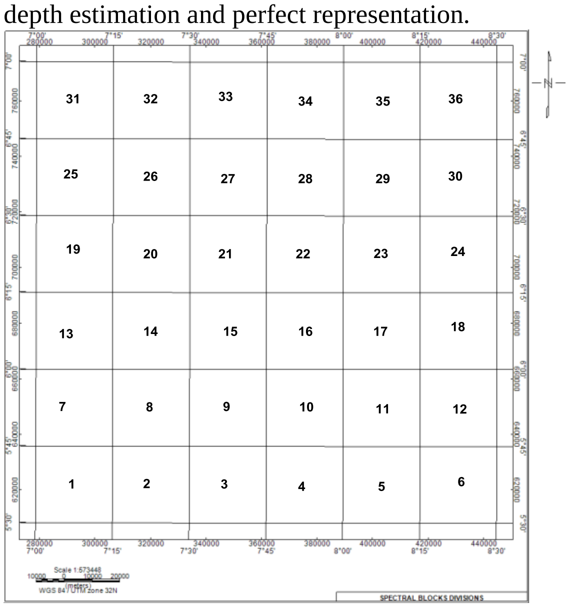

Figure 5: Spectral block schematics over the area

The geothermal gradient defined in equation (2) is related to the Curie temperature θ_c as shown in equation 3 θ_c is as defined in equation 3 (Okubo *et al.,* 1985)[21]

$$\theta_c = \left[\frac{dT}{dZ}\right] Z \qquad (3)$$

Therefore

$$\therefore \frac{dT}{dZ} = \frac{\theta_c}{Z} \qquad (4)$$

$$Z = 2Zc - Z_b \qquad (5)$$

where Z_c= Depth to centre of the magnetic source, Z_b = Depth to the boundary of the magnetic source and Z is the Curie point depth which was computed from the depths obtained from the spectral analysis.

The heat flow (q) was thereafter obtained using Fourier's law in equation 6

$$q = \lambda \frac{dT}{dZ} \qquad (6)$$

where λ is the coefficient of thermal conductivity and it ranges between 2 to 2.5 W/km.ºC(Bello *et al.,* 2017)[22]. The results were thereafter tabulated and mapped.

RESULTS AND DISCUSSION

The Curie Point Depth (CPD), Geothermal Gradient and the Heat flow is as tabulated in table 1. Their maps are respectively shown in figures 6-8.

Table 1: Geothermal and heat flow values of the study area.

SPECTRAL BLOCK	X UTM	Y UTM	Curie Point Depth (km)	Geothermal Gradient (°C/km)	Heat flow mW /m^2
1	292171.1	622276.4	7.426276	76.75449	191.8862
2	320055.1	622276.4	9.151114	62.2875	155.7187
3	347939.1	622276.4	10.73708	53.08705	132.7176
4	375823.1	622276.4	10.04073	56.76877	141.9219
5	403707.1	622276.4	7.070974	80.61124	201.5281
6	431591.1	622276.4	9.61532	59.2804	148.201
7	292171.1	650160.4	13.72495	41.53021	103.8255
8	320055.1	650160.4	7.875448	72.37683	180.9421
9	347939.1	650160.4	9.748402	58.47112	146.1778
10	375823.1	650160.4	9.645844	59.09281	147.732
11	403707.1	650160.4	9.150148	62.29407	155.7352
12	431591.1	650160.4	9.131612	62.42052	156.0513
13	292171.1	678044.4	8.555194	66.62619	166.5655
14	320055.1	678044.4	8.553978	66.63566	166.5892
15	347939.1	678044.4	8.010142	71.15979	177.8995
16	375823.1	678044.4	8.931224	63.82104	159.5526
17	403707.1	678044.4	8.76389	65.03961	162.599
18	431591.1	678044.4	8.906836	63.99579	159.9895
19	292171.1	705928.4	9.19406	61.99655	154.9914
20	320055.1	705928.4	8.012556	71.13835	177.8459
21	347939.1	705928.4	10.7254	53.14488	132.8622
22	375823.1	705928.4	8.976062	63.50224	158.7556
23	403707.1	705928.4	9.31804	61.17166	152.9292
24	431591.1	705928.4	7.021264	81.18196	202.9549
25	292171.1	733812.4	9.55048	59.68286	149.2072
26	320055.1	733812.4	8.171418	69.75533	174.3883
27	347939.1	733812.4	8.525216	66.86048	167.1512
28	375823.1	733812.4	8.473414	67.26923	168.1731
29	403707.1	733812.4	7.24022	78.72689	196.8172
30	431591.1	733812.4	5.602328	101.7434	254.3585
31	292171.1	761696.4	11.82096	48.21943	120.5486
32	320055.1	761696.4	9.032672	63.10425	157.7606
33	347939.1	761696.4	7.69319	74.0915	185.2288
34	375823.1	761696.4	6.668644	85.47465	213.6866
35	403707.1	761696.4	6.926754	82.28963	205.7241
36	431591.1	761696.4	8.084246	70.5075	176.2688
Max value			**13.72495**	**101.7434**	**254.3585**
Min Value			**5.602328**	**41.53021**	**103.8255**
Average			**8.826404**	**66.98388**	**167.4597**

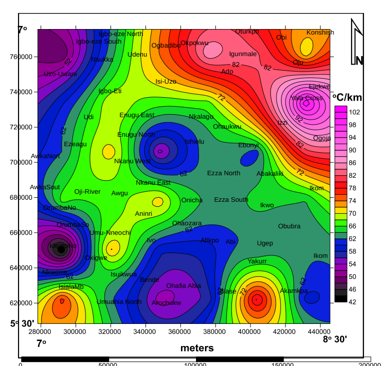

Figure 6: The Curie Point Depth map of the study area

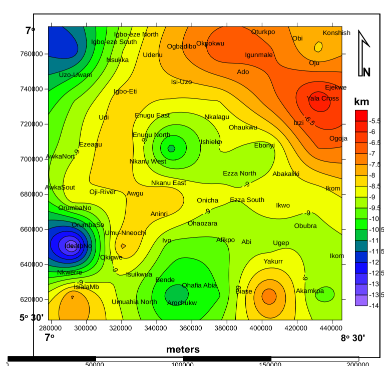

Figure 7: The Geothermal Gradient map of the study area.

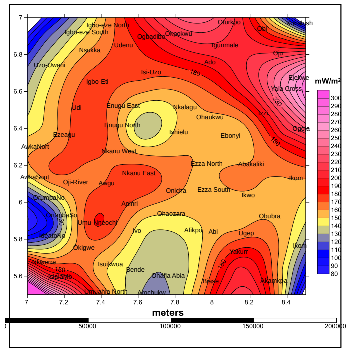

Figure 8: The heat flow map of the study area

Areas with short wavelength anomaly have shallow Curie point depth, hence the effect of near surface magnetic intrusions largely affect the depth of magnetism loss. The shallower the magnetic source the shallower its Curie depth or the higher its tendencies to lose its magnetism compares to others at deeper occurrence depth.

The curie depth value for the study area ranges from 5.6 km to a depth of 13.5 km with an average depth of 8.8 km (Figure 6). The NE area of the composite sheet have Curie Point Depth between -8.5 km and – 5 km these areas include Igunmale, Ejekwe, Udeni, Obi, and North of Nkalagu, West of Akamkpa, North-eastern part of Okigwe, Udi. This implies that rocks in these areas will lose their magnetism at depths shallower than others. However, the extremely deep Curie point depths are found in the NW areas of the composite sheet near Nsukka, and Ideato. Other areas fall within the average range they including Okigwe, Ugep, Nsukka, Enugu North, Umuahia North, Afikpo and South western parts of Ebonyi.

Furthermore, the geothermal gradient of the area shows similar variation pattern with the Curie point depth. The geothermal gradient value of the area ranges from 42 to 102 ^{O}C/km with an average of 73 ^{o}C/km. It represents the increase in temperature with increasing depth, higher geothermal gradient is observed in areas with most high level of intrusive than others. These high geothermal gradient values are seen mostly in North-eastern part of the composite sheet (Igunmale, Ejekwe and others) where most of the high amplitude and short wavelength signals which are indication of near surface basement intrusions are prominent as seen in figure 7**.** These appear to have a very thin crust and hence the earth's mantle and core are not deep hence heat flow is more rapid with increasing depth.

The Heat flow calculated over the area of study shows variation from one place to another, these values ranges from 103.80 mW/m^2 to 254.4 mW/m^2 with an average value of 167.5 mW/m^2 as seen in table 1, the values were plotted in figure 8 as a map. Area with high heat flow are Ejekwe, Igunmale and Obi, Oju, Udeni area found in the North and North eastern part of the area, as heat is said to flow from a region of high temperature to area with low temperature. Areas with low heat flow rate are within the range of 130 to 180 mW/m^2.

From the foregoing, areas with high geothermal gradient also shows high heat flow, this is because the geothermal gradient is an increase in temperature with depth and hence heat flows from areas where temperature is high with increasing depth to where the temperature is low with increasing depth, one of the main factors responsible for the temperature increment in those areas are the effect of high level magmatic intrusions (Near surface occurrence) which serves as conductor of heat from the core to the crust and also the thinness of the curst at these areas. Factors such as the high presence of radioactive element within the sediments that are associated with magmatic deposits also give rise to high geothermal gradient and heat flow.

CONCLUSION

The geothermal gradient and heat flow studies were carried out in the study area and the curie point depth was observed to be in the range of 13km to 5.6 km with a average of 9 km. It was observed that the areas with shallow magnetic sources have low curie depth points, this means that the basement rock within this areas will lose their magnetism at depth shallower than others, the average geothermal gradient over the areas is 66.98 ºC/km areas with the highest shallow currie depth appears to have higher geothermal gradients, this means that the rate of heat energy increase with depth within this axis is great and it is likely due to the conductive nature of the magmatic basement as heat energy are being transferred from the core and mantle region to the crust by conduction via the series of structurally emplaced near surface basement rocks and also likely occurrence of radioactive minerals associated with magmatic emplacement within sedimentary environment which tend to increase the ambient temperature, hence the rate of heat flow in the areas rages from 103.82 mW/m^2 to 254.35 mW/m^2, and an average heat flow rate over the entire area is 167.45 mW/m^2 the areas with high temperature gradient (Geothermal gradient) have also high heat flow rate as heat energy are being transferred from areas with high heat energy to with low heat energy.

The hydrocarbon implication of this can be deciphered when compared with the work of Emujakporue *et al.,* (2014)[23] who related the geothermal gradient and he discovered that liquid hydrocarbon window is shallow in wells with high geothermal gradients and deep in well with low geothermal gradient within an area. He calculated the average geothermal gradient of 23.56 ºC/km and range of 13.46 ºC/km to 33.66 ºC/km.

It can therefore be concluded that regions with high geothermal gradient are of better prospect for shallow depth hydrocarbon accumulation as the temperature of hydrocarbon maturity is attained faster. However, in areas with thick sediments accumulation increase in depth to basement also leads to increase in temperature, the presence of thick sediments do influence the temperature, as they serve as conductors and conduit of heat dissipation for the heat which is generated by radioactive decay within the deep basement rock, but the occurrence of higher geothermal gradient is observed in areas with shallow basement as the sedimentary cover is thin, and there is less of heat dissipation and hence the increase in geothermal gradients.

Therefore Igunmale, Ejekwe, Oju, Ogoja and Oturkpo areas with high geothermal gradients are areas of geothermal prospects with volcanic activities. They also may have thick layer of thermally insulated sediments cover. Conversely, Ideato, Orumba, Uzo-Uwani, Arochukwu and Ikom with low geothermal gradients are not geothermal prospect areas.

The average heat flow obtained from the study ranges from 103.8-254.4 mW/m^2 with an average value of 167.5 mW/m^2 which is typical of a continental crust (Jessop *et al.,* 1976)[24]. The variations in the heat flow indicate a random distribution of magma conduits.

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