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Integration of Aeromagnetic Interpretation and Induced Polarization Methods in Delineating Mineral Deposits and Basement Configuration within Southern Bida Basin, North-West Nigeria

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Abstract

Aeromagnetic data interpretation and Induce Polarization (IP) method has been integrated and interpreted with a view of delineating magnetic minerals within some part of the Southern Bida Basin, Nigeria. Spectral analysis method was used in delineating the depth to magnetic basement and model prominent magnetic anomaly. Analysis of Induce Polarization data were used in delineating the potential fractures zones of mineralization. Visual inspection of the magnetic anomalies and first vertical derivative maps reveals that the area is highly faulted with major faults trending East-West (E-W) and minor ones Northeast-Southwest (NE-SW) directions. The qualitative interpretation results of both the resistivity and chargeability pseudosections reveal potential fractures zones trending East-West (E-W) and the depth to the anomalous body ranges from (0.3-2.5 km) with average overburden thickness of 2.1 km. Two depth source models were interpreted using Discrete Fourier Transform method (spectral analysis) namely; the shallower sources which range from 0.45 to 1.49 km and the deeper ones which range from 1.81 to 3.24 km. The quantitative interpretation of the aeromagmatic data, depict that the average sedimentary thickness ranges from (2.3-3.2 km) and the average depth to the Curie isotherm in the area is 24.76 km. The result also shows that the Curie temperature isotherm within the basin is not a horizontal level surface, but is undulating. The regional average results for both geothermal gradient and heat flow across the study area are 23.07°C/km and 57.66 W/m² respectively. Based on the computed sedimentary thicknesses (2.3-3.2 km), the geothermal gradient (22.27 and 37.00°C/km.) and the prevalent fractures, the possibility of hydrocarbon accumulation in the northern and southeastern part of the study area is feasible whereas other parts of the study area with low sedimentary thicknesses will favour magnetic mineral deposits such as the prevalent oolitic iron ore deposits at Agbaja and Kotonkarifi axes.

Keywords: Spectral analysis; Geothermal gradient; Curie isotherm, Heat flow, Chargeability and resistivity psuedosection

Introduction

There is no doubt that petroleum has contributed substantially to Nigerian revenue since its discovery in 1956. However, the perennial crash of crude oil prices all over the world has pushed the stakeholders and researchers attention towards non-oil revenue generation such as solid minerals [1]. Again, despite that a greater part of Nigerian landmass is underlain by basement rocks, the search for geothermal energy has not received enough attention, thus, there is gap in crustal temperature information across the country. More so, in view of increasing environmental pollution associated with exploration and consumption of hydrocarbon as well as decline in its production in Nigeria, it is prudent to explore renewable and cleaner sources of energy such as geothermal energy for satisfaction of human energy needs [2,3].

It should be noted however that target detection is usually impossible using a single geophysical method, since identical geophysical anomalies may be related to an anomaly source with different physical properties, mode of occurrence pattern and nature [4,5]. Thus, integration of geophysical methods is necessary in order to reveal and characterize hidden targets like the simultaneous measurement of induced polarization and aeromagnetic anomaly interpretation for better interpretation of the observed anomalies. Nevertheless, the study focuses on integrating Induce polarization method and aeromagnetic interpretation over the Bida basin. Spectral analysis of magnetic survey has proven to be a powerful and convenient tool in the processing and interpretation of potential field geophysical data [2,6]. It seeks to describe the frequency content of a signal based on a finite set of data. Its advantage is that the spectral domain expressions of the anomalies are generally simple as compared to the expressions of the anomalies in the space domain. This will delineate the configuration of the Basin itself by determining the depth to magnetic basement. It will also establish the structural features and possibly obtain a 3-Dimensional view of the Basin, the geothermal gradient and the curie-point isotherm depth of the basement rocks and mineral deposits respectively. It is against this background that this study becomes apparent.

All the previous works in the Bida Basin are preliminary in nature. None of this work discusses the minerals potential of the Bida Basin in details. This is because the data were scanty and did not include detailed geophysical interpretation and there is no detailed ground survey such as IP to map the mineral and to delineate the configuration of the basin its self. Again, there are scarce records of crustal temperature studies in the study area. Hence, Curie temperature depth in conjunction with heat flow assessment would significantly complement the geophysical information of the area to bridge the gap of lack crustal temperature records. The present study will be beneficial to Nigerians as the

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exploitation of possible geothermal potentials could be a vital alternative to other energy sources (such as petroleum, solar, and wind).

The aim of this study was to delineate the mineral potential of some parts of the Southern Bida Basin using an integrated method of aeromagnetic and Induced Polarization (IP) techniques. The specific objectives are to: produce the residual anomaly maps; determine the depths to the Curie-temperature isotherm in the area; determine the geothermal gradient and mantle heat flow values; delineate the zone of mineralization from the IP interpretation; delineate the fault trends and areas with geothermal energy potential and its attributes; generate model for possible areas of mineral deposits.

Geology and the Study Area

The study area falls within the southern Bida Basin, which is a NW-SE trending intracratonic structure extending from slightly south of Kontagora in Niger State in the north to the area slightly beyond Lokoja (Kogi State) in the south Obaje [7]. Although, there is no clear boundary between the Northern and Southern Bida Basin. The geographical coordinates of the study area lie between 5°30' and 7°30' of longitude and between 7°30' and 9°00' N of latitude, covering an area of approximately 27,225 km². The major towns are Bida, Abaji, Pategi, Baro, Gulu, Kotonkarifi, Lokoja and Kabba (Figure 1).

According to Obaje [7], the Southern Bida Basin consists of Lokoja Formation which is overlain by Patti Formation and the Patti Formation is as well overlain by the Agbaja ironstone Formation (Figure 1). Akande [1] and Obaje [7] believe that the Campanian Nkporo and Enugu Formations have some lateral equivalents in the Lokoja Formation of the Bida Basin. Overlying the sedimentary units of the Mamu Formation are those whose lateral equivalents are the conglomerates, cross-bedded and poorly sorted sandstones and clay stones of the Lokoja and Bida Formations and partly the Patti Formation in the Bida Basin. The Mamu Formation is succession by sandstones of the Lower Maastrichtian Ajali Formation laterally equivalent to the Patti, Sakpe and Enagi Formations of the Bida Basin. The Patti and Enagi Formations are overlain by the Agbaja and Batati Formations (lateral equivalents) of Upper Maastrichtian age

Materials and Methods

The methodology involved the use of nine aeromagnetic maps which were collated and digitized in order to produce total magnetic intensity map that formed the input data for the separation of both the regional and residual magnetic anomalies in this study. Then, the residual anomaly formed the input data for spectral analysis. This was used to compute depth to the basement, deduce the prevalent igneous terrain and delineate Curie-temperature isotherm, geothermal energy potential and mantle heat flow. Finally, the potential zones of mineralization were delineated using spectral analysis and IP interpretation deductions (Figure 2).

The nine aeromagnetic maps obtained were digitized along the





flight lines at 2 km intervals and the intersection points were picked and contoured by use of contouring software (Oasis Montaj). The contoured data which is referred to as the Total Magnetic Field Intensity (TMI) of the study area contains both the regional and residual anomaly. Then a linear trend surface was generated (Eq. 1) and fitted on to the digitized aeromagnetic data by removing the regional magnetic gradient in order to obtain the residual anomaly map (Figure 3a) that would be interpreted.

$$Z(x,y) = 1.1088x + 65.53y + 2512.029$$
(1)

Consequently, the thirty-seven anomalous targets were revealed from the seven profiles taken within the residual map (Figure 3b), which were subjected to spectral analysis in accordance with the guiding principles given by many authors such as Bhattacharyya and Leu [8], Spector and Grant [9], Okubo [10], Onwuemesi [11], Chinwuko [12], Chinwuko [13], Anakwuba and Chinwuko [2] and others. Spectral analysis gives a procedure for quantitative analysis of complex aeromagnetic data sets. The natural logarithm of the amplitude is plotted against the Nyguist frequency (Figure 4). The slope of each segment provides information about the depth to the top of an ensemble of magnetic or gravity bodies.

For generating the spectral analysis for curie isotherm, Bhattacharyya and Leu [8] method was adopted. The first step according to Bhattacharyya and Leu [8] is to estimate the depth to centroid (Z_0) of the magnetic source from the slope of the longest wavelength of the spectrum that is given below:

$$In\left[\frac{\rho(\sqrt{S})}{/S/}\right] = InA - 2\pi / S / Z_{o}$$
⁽²⁾

Where,

P(s) is the radially averaged power spectrum (natural log of amplitude) of the anomaly /s/ is the wave number (Nyguist frequency) and A is a constant.

The second step is the estimation of the depth to the top boundary (Z_t) of that distribution from the slope of the second longest wavelength spectral segment [10],

$$In\left[\frac{\rho(\sqrt{S})}{/S/}\right] = InB - 2\pi / S / Z_t$$
(3)

Where,

B is the sum of constants independent of /s/.

Then, the basal depth (Z_b) of the magnetic source was calculated from the equation of Bhattacharyya and Leu [8] as shown below:

Page 4 of 13



 $Z_{b} = 2Z_{o} - Z_{t}$ (4)

The obtained basal depth (Z_b) of magnetic sources in the study area is assumed to be the Curie point depth according to Bhattacharyya and Leu [8].

Hence, the heat flow and thermal gradient value was calculated in the study area using an equation expressed by Fourier's law as follows:

$$q = \lambda \frac{dT}{dZ}$$
(5)

Where,

Q: the heat flow and λ is the coefficient of thermal conductivity.

According to Tanaka [14], the thermal gradient (dT/dZ) can be estimated using equation 6, where we have the Curie temperature (θ) and the Curie point depth (Z_b) available:

$$\theta = \left\lfloor \frac{dT}{dZ} \right\rfloor Z_b \tag{6}$$

The mathematical background used in this work is the time domain

method. In the time domain, chargeability (M) is commonly used and it's measured in mV/V. It is expressed as:

$$M = \frac{V_p}{V_o}$$
(7)

Where,

V_p: the over-voltage at time.

V_o: the observed voltage with an applied current.

There is great difficulty measuring of V_p at the moment the current is switched off, it is measured at a fixed time after cut-off and this gives rise to apparent chargeability defined as;

$$M_a = \frac{1}{V_o} \int V_p(t) dt \tag{8}$$

Where,

 $V_{p}\left(t\right)\!\!:$ is the over-voltage at time t, and other terms as earlier defined.







Page 6 of 13

Results and Discussion

Qualitative interpretation of the aeromagnetic data

The qualitative interpretation is done by visual inspection of the Total Magnetic Intensity (TMI), residual anomaly, analytic signal, and first vertical derivative maps [4,15]. The maps show that the total magnetic field and residual anomalies (Figures 3a, 5) range from 7500 to 8800 nT and -1200 to 400 nT respectively. Thus, the maps show areas with low and high both maps revealed that at southeastern parts comprising Ikole-Kabba intensity of magnetization respectively. Kotonkarifi axis, there are strong evidence of higher magnetic intensity as well as numerous anomalous bodies within the area. Also, the contour lines are closely spaced signifying that the depths to basement around these areas are relatively shallow based on the visual interpretation.

The result of qualitative interpretation also revealed that the area is intensely faulted with major faults trending East-West (E-W) and minor ones Northeast-Southwest (NE-SW) directions using visual inspection of the magnetic anomalies maps (Figures 3a & b). There is strong evidence of higher magnetic intensity as well as numerous anomalous bodies within the area. Biswas and Acharya [16], believes that contour lines which are closely spaced signifying that the depths to basement around these areas are relatively shallow and that closely spaced linear sub-parallel orientation of contours which are found in the north eastern and south eastern parts of the study area suggests that faults or local fractured zones may possibly pass through these areas. However, at the Central and Northern parts, the contour lines are widely spaced signifying that the depths to basement are relatively high in these areas namely: Isanlu, Aiyegunle, Pategi, Baro and Gulu areas (Figure 5). Biswas [17,18] generally believed there would always be a magnetic susceptibility contrast across a fracture zone due to oxidation of magnetite to hematite, and/or infilling of fracture planes by dykelike bodies whose magnetic susceptibilities are different from those of their host rocks. Such geologic features may appear as thin elliptical closures or nosing on an aeromagnetic map. Most of the anomalous features trend in the Northeast-Southwest and minor ones trend East-West directions.

Also, the residual anomaly map (Figure 3b) shows positive magnetic anomaly and larger sedimentary thickness indicating deeper depths at the northern and central portions. In the central part of the study area there is a dye-shaped linear feature and fractures (Figures 3a & b). The fact that this structure is associated with Bida Basin makes it more desirable for further study. Several contour closures are found Southeastern and northeast of this area, which indicate shallow basement.

Qualitative interpretation of the IP result

The IP results are qualitatively interpreted by visual inspection of both the resistivity and chargeability psuedosection of the IP data. Low resistivity and low chargeability value show mineralized zone, while high resistivity and chargeability value corresponds to low conductivity. Six IP profiles where carried out, mainly within the south-eastern part of the study. The data obtained are consequently plotted with Ip2win





software (Figure 6). Qualitative interpretation of both the resistivity and chargeability pseudosections also reveals potential fractures zones trending East-West (E-W) and the depth to the anomalous body ranges from (0.3-2.5 km) with average overburden thickness of 2.1 km. The average resistivity and chargeability values ranges from (5.17 to 42.4 Ω m) and (1.10 to 42.3 m/sec) respectively.

Quantitative interpretation of the aeromagnetic data

The reason behind quantitative interpretation is to obtain information about the depth to magnetic body, its shape and size, and probably details about its magnetic susceptibility [19]. The most important essence of quantitative interpretation is the determination of depth to the anomalous body due to the obvious importance of the thickness of the sedimentary section to the petroleum geophysicist, the depth to source normally referred to as the depth to the magnetic basement, is of vital importance. Depth information may also be important when potential mineral deposits are covered by thick layer of consolidated or unconsolidated overburden.

The seven profile lines (Figure 7) in the residual magnetic map reveals a total of thirty seven (37) (Figure 5) anomalies. The anomalies were subjected to spectral analysis to estimate depth to the magnetic source (sedimentary thickness) around the studied area (Figure 8). These profiles were taken perpendicular to the direction of the magnetic anomalies. The method was chosen because of its advantage of filtering all the noise away from the data. Secondly, during the application of this method, information is not lost in the process unlike other methods. The graphs of the natural logarithms of the amplitude against frequencies obtained for the seven profiles were plotted. Linear segments from the low frequency portion of the spectral, representing contributions from the deep-seated causative bodies were drawn from each graph. The gradient of the linear segments were evaluated and the depth to magnetic sources were determined along the selected profiles (Figure 8).

Spectral analysis results reveals two depth sources in the area namely; the shallower sources which range from 0.45 to 1.49 km at the Southern parts of the study area ; while the deeper ones which range from 1.81 to 3.24 km at the northern parts. The result of the analysis also shows that depths to the centroid and magnetic bodies (sedimentary thicknesses) range from 9.09 to 16.84 km and 0.5 to 3.2 km respectively.

The Curie isotherm depth is shallower at the northwestern part (precisely at Isanlu and Pategi areas) with curie depth ranging from 16.0 to 23.0 km while at the other parts, the Curie isotherm depth is deeper and it ranges from 24.0 to 32.0 km. The average depth to the Curie isotherm in the area is 24.76 km. The result also shows that the Curie temperature isotherm within the basin is not a horizontal level surface, but it is undulating. The geothermal gradients across the study area obtained ranges between 17.17 and 37.00°C/km with a regional average of 23.07° C/km. The result of the heat flow across the study area obtained ranges between 42.93 and 92.50 W/m² with an average of 57.66 W/m² (Table 1).

Furthermore, Correlating geothermal gradient and Heat flow show a positive relationship (Figure 9a). This suggest that area of higher geothermal gradient corresponding to area of heat flow and this may favour hydrocarbon generation while area of low heat flow showing low geothermal gradient may not favour hydrocarbon generation. While

Page 7 of 13

Correlating Curie point depth and Heat flow show a negative or inverse relationship (Figure 9b). From the relationship, area of high Curie point depth reveals low Heat flow (Kabba, Kotonkarifi and Lokoja). These areas correspond to area of low sedimentary thickness (shallower depth to basement) (Figures 9c & d). While, area of low Curie point depth reveals high heat flow (Isanlu, Baro and Aiyegunle) and deeper depth to



Figure 7: Residual anomaly map with seven profiles taken within the study area (Contour interval ~20 nT).

basement (higher sedimentary thickness). The geologic implications of this is that area of higher Curie point depth and low heat flows are area of higher magnetic intrusions. While area of low curie point depth and higher heat flow may support hydrocarbon generation [4].

The study area is highly fractured with most of the fracture trending in the E-W direction and minor ones in NW-SE direction. The stratified nature of the shales and sandstones may likely favour migration of fluids into the potential reservoir rocks made up mainly of fluvial, shelf and flood plain sandstones in the Lokoja and the Patti Formations. Also established four different trap configurations that are possible in the Bida Basin namely; traps within uplifted blocks, traps in drapes and/or compacted structures over deep horsts, traps in structures developed along major faults and lineaments, and stratigraphic traps along flanks of uplifted blocks. These traps are enhanced by regional seals provided by the shales, siltstones and claystone of the Patti and Agbaja Formations.

However, based on the computed sedimentary thicknesses (2.3-3.2 km), the geothermal gradient (17.82 and 37.00°C/km.) and the prevalent fractures which may serve as migratory pathway for hydrocarbon or hydrothermal fluid, then the possibility of hydrocarbon generation in the northern and Southeastern parts of the study area is feasible. It is also good to note that Emujakporue and Ekine [20] suggested possible hydrocarbon accumulation within the southern Bida Basin. All these deductions were reached after due consideration of qualitative and quantitative interpretations supported by geological information of the area (Figures 10a & b).

However, those region of where there are low sedimentary thicknesses and it is supported by the IP interpretation are the region that housed mineral ore deposits within the study area (Figure 11).



Page 9 of 13

Anomaly	Depth to the Top (km)	Depth to the Bottom (km)	Curie Point Depth (km)	Geothermal Gradient	Heat Flow (Wm ²)
1	2.09	14.73	27.37	20.1973	50.49324
2	3.11	12.84	22.57	24.49269	61.23172
3	1.49	15.11	28.73	19.24121	48.10303
4	0.96	13.45	25.94	21.31072	53.27679
5	2.42	12.88	23.34	23.68466	59.21165
6	3.18	10.06	16.94	32.63282	81.58205
7	3.05	13.92	24.79	22.29931	55.74829
8	1.52	12.87	24.22	22.82411	57.06028
9	1.14	14.31	27.48	20.11645	50.29112
10	1.08	12.95	24.82	22.27236	55.6809
11	0.53	16.28	32.03	17.25882	43.14705
12	2.46	12.21	21.96	25.17304	62.9326
13	3.22	11.04	18.86	29.31071	73.27678
14	3.07	14.53	25.99	21.26972	53.1743
15	1.49	16.84	32.19	17.17304	42.93259
16	0.45	15.06	29.67	18.63161	46.57904
17	2.71	13.01	23.31	23.71514	59.28786
18	3.24	9.09	14.94	37.00134	92.50335
19	3.19	11.23	19.27	28.68708	71.7177
20	2.85	13.69	24.53	22.53567	56.33918
21	2.25	14.47	26.69	20.71188	51.77969
22	2.33	12.61	22.89	24.15028	60.37571
23	2.08	11.89	21.7	25.47465	63.68664
24	2.86	14.05	25.24	21.90174	54.75436
25	3.23	13.11	22.99	24.04524	60.11309
26	2.98	9.47	15.96	34.63659	86.59148
27	1.81	13.22	24.63	22.44417	56.11043
28	1.65	16.51	31.37	17.62193	44.05483
29	2.13	14.83	27.53	20.07991	50.19978
30	3.17	16.32	29.47	18.75806	46.89515
31	3.22	11.63	20.04	27.58483	68.96208
32	2.08	13.83	25.58	21.61063	54.02658
33	2.01	12.94	23.87	23.15878	57.89694
34	2.14	15.77	29.4	18.80272	47.0068
35	2.33	13.22	24.11	22.92825	57.32061
36	2.79	15.64	28.49	19.4033	48.50825
37	2.47	14.85	27.23	20.30114	50.75285
Average	2.29135135	13.52594595	24.76054054	23.066	57.66499

 Table 1: Curie point depth estimation from spectral analysis.







Figure 9b: The Curie Depth map and Real view model of the study area (Contour interval ~1 km).



Figure 9c: Geothermal gradient map and real view model of the study area (Contour interval ~1°C/km).



Page 11 of 13







Conclusions

Analyzing of Induce Polarization (IP) and aeromagnetic anomalies over the southern Bida Basin has been carried out in order to pinpoint zones of high mineral potential and the conclusions are as follows:

The maps show that the total magnetic field and residual anomalies range from 7500 to 8800 nT and -1200 to 400 nT respectively. Both maps revealed that at southeastern parts comprising Ikole-Kabba-Kotonkarifi axis, there are strong evidence of higher magnetic intensity as well as numerous anomalous bodies within the area.

The result also reveals contour lines are closely spaced signifying that the depths to basement around these areas are relatively shallow based on the visual interpretation, whereas at the central and northern parts, the contour lines are widely spaced signifying that the depths to basement are relatively high in these areas namely: Isanlu, Aiyegunle, Pategi, Baro and Gulu areas.

The result of qualitative interpretation reveals that the area is intensely faulted with major faults trending East-West (E-W) and minor ones North East-South West (NE-SW) directions.

Spectral analysis results reveals two depth sources in the area namely; the shallower sources which range from 0.45 to 1.49 km at the Southeastern and Southern parts (including Ikole, Kabba, Kotonkarifi and Lokoja areas) while the deeper ones which range from 1.81 to 3.24 km at the northwestern and northern parts (including Isanlu, Pategi, Baro and Gulu areas).

Qualitative interpretation of both the resistivity and chargeability pseudosections also reveals potential fractures zones trending East-West (E-W) and the depth to the anomalous body ranges from (0.3-2.5 km) with average overburden thickness of 2.1 km. The average resistivity and chargeability values ranges from (5.17 to 42.4 Ω m) and (1.10 to 42.3 m/sec) respectively.

The result of the analysis also shows that depths to the centroid and magnetic bodies (sedimentary thicknesses) range from 9.09 to 16.84 km and 0.5 to 3.2 km respectively. The Curie isotherm depth is shallower at the northwestern part (precisely at Isanlu and Pategi areas) with curie depth ranging from 16.0 to 23.0 km while at the other parts, the Curie isotherm depth is deeper and it ranges from 24.0 to 32.0 km. The average depth to the Curie isotherm in the area is 24.76 km.

The result also shows that the Curie temperature isotherm within the basin is not a horizontal level surface, but it is undulating and the geothermal gradients across the study area obtained ranges between 18.82 and 32.03° C/km.

The study area is situated within the sedimentary terrain that is surrounded by some parts of Basement Complex of Nigeria which pave way for some prevalent intrusive within some parts of the study area. However, the present study has been able to identify these areas with igneous intrusive which are to be avoided during search for hydrocarbon.

Based on the computed sedimentary thicknesses (2.3 to 3.2 km), the geothermal gradient (18.82 and 32.03°C/km) and the fractures which serve as migratory pathway for hydrocarbon or hydrothermal fluid, then the possibility of hydrocarbon generation in the northern and Southeastern part of the study area is feasible.

Recommendations

▶ No single geophysical method is ever conclusive so there is

a great need to integrate more geophysical methods in other to reveal clearly the zones of good mineral and hydrocarbon potential of the study area.

Page 12 of 13

Core drills sample of the area or cuttings in future wells will help to ascertain the ages of the section using biostratigraphy.

> The aeromagnetic interpreters must be able to identify and eliminate all events relating to noise.

> There is a great need to combine and employ other geological skills and knowledge such as sedimentology, stratigraphy, and structural geological for effective interpretation and deductions.

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