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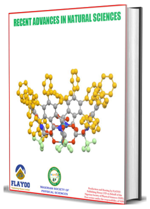

Spectral analysis of aeromagnetic data over parts of Southwestern Nigeria

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ABSTRACT

This study endeavors to assess spectral depths, explore Basement structure variability, and deduce geothermal heat distribution by determining Curie point depth (Z_b) through aeromagnetic data analysis across 14 sheets in Southwestern Nigeria. The depths to the shallow magnetic source (Z_t) range from 0.14286 km to 1.02632 km, indicating sediment thickness, with the deepest point situated in the Northwestern region and progressively shallower towards the central and Southern portions of the study area. Depths to the deeper magnetic source (Z_0) span from 1.08333 km in the North-central part to 3.23529 km in the Southwestern part. The primary sources of the first layer (Z_t) depth are intrusions/outcropping Basement rocks, while the second layer (Z_0) results from the intrusion of magnetic rocks into the basement, intra-Basement fissures, and deeper magma intrusions below the bedrock. Curie point depth ranges from 1.87380 km to 6.25629 km, with the North-central region exhibiting the shallowest depths, followed by the Northeast, Northwest, and Southeast. Shallow Curie point depth is attributed to magma upwelling and magmatic intrusion in highly fractured quartzite units and older granite units, while deeper Curie point in the Southwestern part may result from isostatic compensation/recovery. Given that Curie point depths are shallower than 10 km, the study area holds geothermal resource potential, particularly in the North-central region. The correlation between estimated spectral depths from aeromagnetic data and observed geothermal signatures in the study area promises to be advantageous in the pursuit of alternative energy generation, potentially mitigating the effects of global warming.

1. INTRODUCTION

Geophysical exploration techniques have employed spatial surveys of variations on the earth's magnetic field strength across a number of years [1]. The variations on the earth's magnetic field strength is due to the corresponding variations in the magnetic behavior of subsurface rocks; a property which provides information that enables the determination of depth to the bedrock and thickness of sedimentary layer. The spatial variations on the earth's magnetic field strength can also be used to identify faults, shear, and fracture zones which serve as possible site for a range of mineral reserves and subsequently influence exploration for minerals brought on by epigenetic stress in the nearby rocks [2]. The method of magnetic prospecting is also used for locating bodies of igneous and metamorphic rocks and a times sedimentary rocks with banded iron formations that contains sub-

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stantial storage of magnetite (Fe_3O_4). Meanwhile, magnetite is the most abundant and dominant naturally occurring magnetic mineral source influencing magnetic anomalies across the continental crust [1, 3].

Amidst the aforementioned, one of its greatest potential is its capacity to gauge how deep the magnetic source is vis-à-vis regional temperature distribution at depth. Importantly, the subsurface temperature distribution strongly influences a lot of geodynamic phenomena observed on the lithosphere [4]. Therefore, geothermal assessment in different locations in Africa reflects variabilities of the lithospheric structure. Spectral analysis is performed based on surface measurements of magnetic anomaly, which are regarded as the summation of magnetic fingerprints from all depths. Therefore, estimating spectral depths and the distance to a region's magnetic sources can reveal details about the subsurface thermal property or distribution at depth in the region and by extension the concentration of geothermal energy. This theory agrees with the conclusions by Dolmaz *et al.* [5].

Abraham *et al*. [6] evaluated depth to the magnetic source bottom in Northwestern Nigeria's Wikki Warm Spring Region, the average value was observed to be 10.72 km, while the mean temperature gradient was 54°C/km while the heat flux value is 135.28 mWm^{-2}. Chinwuko *et al*. [7] also carried out spectral analysis and magnetic modelling around Biu-Damboa, Northeastern Nigeria. They opined that a 2.0 D modelling of a tripartite profile suggests mafic rock composition induced magnetic anomalies between 0.67 km and 2.27 km in depth. Also, the existence of massive and continuous distribution of mafic rocks, the majority of which gave birth to the mafic intrusions, indicates that the region is a mantle plume influenced ancient rift. Nwankwo *et al*. [8] determined Curie temperature depth over Nupe Basin in Nigeria's West Central region. According to him, Curie point depth varies between 12 km and 30 km while the corresponding heat flow ranges between 30 mWm^{-2} and 120 mWm^{-2}. This study aims at estimating the spectral depths of the magnetized crust and the evaluation of subsurface heat distribution in our study area using the Curie point depth estimates. The outcome promises to be very useful as an alternative source of electricity generation in Nigeria and Southwestern Nigeria in particular.

2. GEOLOGY OF THE STUDY AREA

The study area is situated between latitudes 6°23′ N and 7°38′ N and longitudes 3°53′ S and 5°8′ S. The main geologic units are the Basement Complex Rocks and Sedimentary Basins (from the Bida Basin) in some parts, but largely underlain by rocks originating from the Migmatite Gneiss - Quartzite Complex. The Precambrian Basement Complex covers about 90% of the entire Southwestern Nigeria (Figure 1) excluding Lagos State and parts of Ondo State, being coastal in nature these two portions form part of the Sedimentary Basin [9]. The Precambrian Basement Complex on the other hand is a component of the Pan African orogenic belt situated between the West African/Congo Cratons and towards the South of Tuareg Shields [10], and inhabits the reactivated region brought about by the plate collisions between active Pharusian continental margin and the more passive continental margin of the West African craton [11]. Fundamentally, the Basement Complex is derived from some key orogenic circles, viz; deformation, metamorphism and remobilization. These cycles are delineated by enormous deformation and isoclinal folding, which gave rise to regional metamorphism, and large-scale migmatization, granitization and gneissification [11, 12].

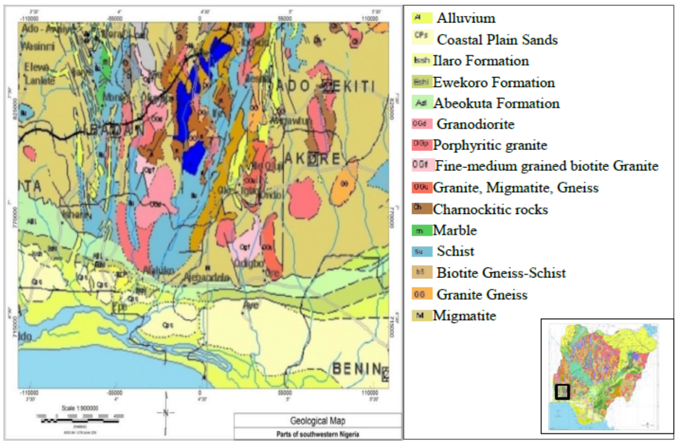

Figure 1. Geological map of the study area (geological survey of Nigeria, 2015).

3. MATERIAL AND METHOD

3.1. MATERIALS

The aeromagnetic data was acquired by Fugro Airborne Survey Services using airborne magnetometer (3x ScintrexCS2 Cesium Vapour), on a map scale of 1: 100000 series (Figure 2), along NW-SE Flight Lines and Tie Line along Northeast (NE) – Southwest (SW) direction with 500 m Flight Line Spacing, Tie Line Spacing of 5000 m, Flight Line Trend of 135 degrees, Tie Line Trend of 225 degrees, Sensor Mean Terrain Clearance of 80 m, at an elevation of 100 m and magnetic data recording interval of 0.05 seconds. For this study, fourteen (14) digital map sheets covering Ibadan (Sheet No. 241), Iwo (Sheet No. 242), Ilesha (Sheet No. 243), Ado-Ekiti (Sheet No. 244), Abeokuta (Sheet No. 261), Ife (Sheet No. 262), Ondo (Sheet No. 263), Akure (Sheet No. 264), Ijebu-Ode (Sheet No. 280), Lekki-Epe (Sheet No. 281), Okitipupa (Sheet No. 282), Siluko (Sheet No. 283), Mahin (Sheet No. 296) and Okowu (Sheet No. 297) were used. Information from the Aeromagnetic Anomaly Data were extracted using GEOSOFT Oasis Montaj. The diurnal magnetic variations and the geomagnetic gradient were also eliminated [13].

3.2. METHODS

3.2.1. Depth to Curie temperature estimation

According to Okubo *et al*. [14], distance to magnetic source (Z_b) is computed in two phases; firstly, slope of the longest wavelengths of the spectrum is used in calculating the deeper magnetic source or depth to the centroid Z_o [14–16] as;

$$\text{In H}(s) = \text{In A} - 2\pi s z_o. \tag{1}$$

In the second stage, slope of the spectral segment with second - longest wavelength is used to calculate depth to the top boundary or shallow magnetic source depth (z_t) of that distribution [14–16]

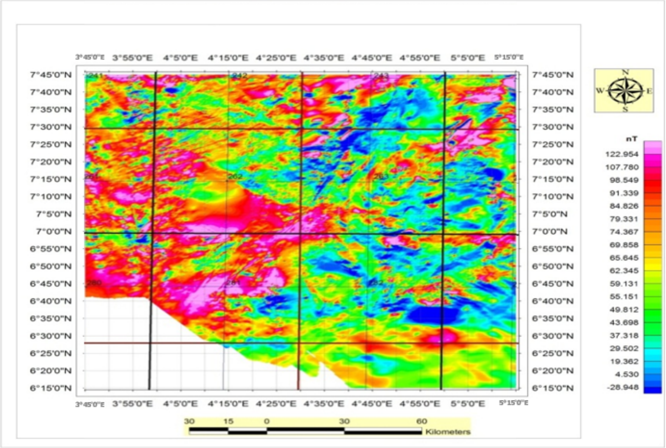

Figure 2. Total magnetic field intensity map of the study area (a constant TMI value of 33,000 nT has been removed).

as;

$$\text{In}\ H(s) = \text{In}\ B - 2\pi s z_t, \tag{2}$$

where A and B are constants that are independent of s, H(s) is radially averaged power spectrum of the anomaly, while s is the wave number. Basal depth of the magnetic sources which is regarded as the Curie point depth (Z_b) is calculated using [14, 17];

$$z_b = 2z_0 - z_t. \tag{3}$$

Finally, the magnetic survey was divided into overlapping subregions from which the spectral blocks were obtained by graphing the logarithm of spectral energies vs frequency on a linear scale, the power spectral analysis of each of the blocks was performed, and data points on the linear segment of the plot attributable to magnetic abnormality resulting from a given depth were located (Figure 3). The Figure shows graph of radially averaged power spectrum using the magnetic anomaly data for spectral block 1. Thus, the plot is divided into sections with varying slopes, and the extent of the slope is used as an indicator of depth in a case where there is a shallow volcanic region overlying a deep Basement [5]. Given a collection of anomalies, the depth factor will be given by exp (-2zk), where z is the average depth per layer. Therefore, a straight line with slope equal to (-2z) would be obtained from the graph of the radial spectrum on a logarithmic scale.

Given slope of the best fit m and the frequency unit expressed in rad./km, the mean depth of burial of the ensemble will be expressed as [2]

$$Z = \frac{-\text{m}}{2}. \tag{4}$$

However, if the frequency is measured in cycles per kilometer, the average depth of burial will be given by [2];

$$Z = \frac{-m}{4\pi}. \tag{5}$$

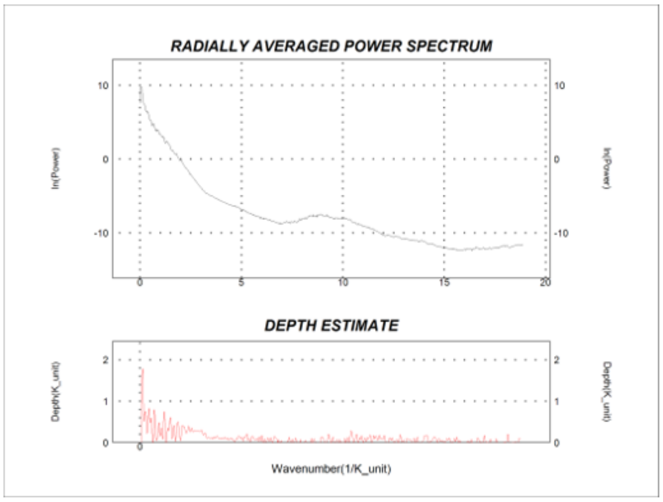

Figure 3. A radially averaged power spectrum for the estimation of Curie Point Depth using two dimensional magnetic anomaly data of spectral block 1.

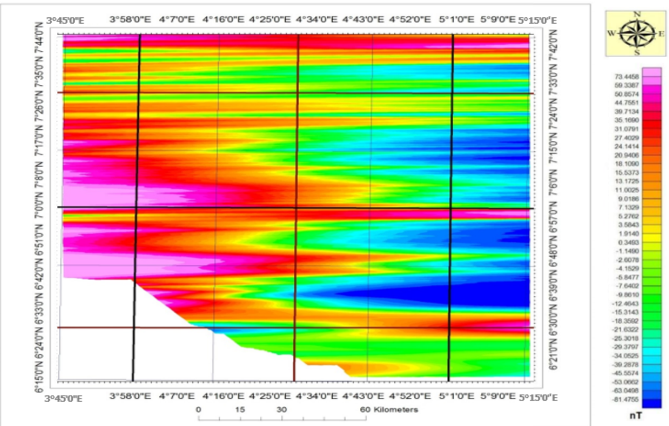

Figure 4. Regional magnetic field intensity map of the study area (A constant TMI value of 33,000 nT has been removed.O)

4. RESULTS AND DISCUSSION

4.1. RESULTS

Total magnetic field data (Figure 2) comprises the summation of effects due to all sub-surface magnetic sources, both long and short wavelengths features which can influence the assessment of depth extent to the centroid [18]. To solve this, we had to eliminate such influence before evaluating the target parameters by separating the residual-regional anomaly (Figure 4) from Total Magnetic Field Intensity (Figure 2) Therefore, the region of no data coverage (bottom left corner) was filtered out. The estimation and subtraction of the regional magnetic field shown in Figure 4, leads to the residual magnetic field map (Figure 5) which corresponds to the target sources. The residual anomaly map reveals precise magnetic anomalies resulting from the heterogeneities in rocks across Basement block interfaces which could have implications in terms of mineral exploration. Hence, the residual magnetic field was subjected to further examination. The result obtained was employed in constructing spectral depth to the top boundary (Z_t) contour (Figure 6), spectral depth to

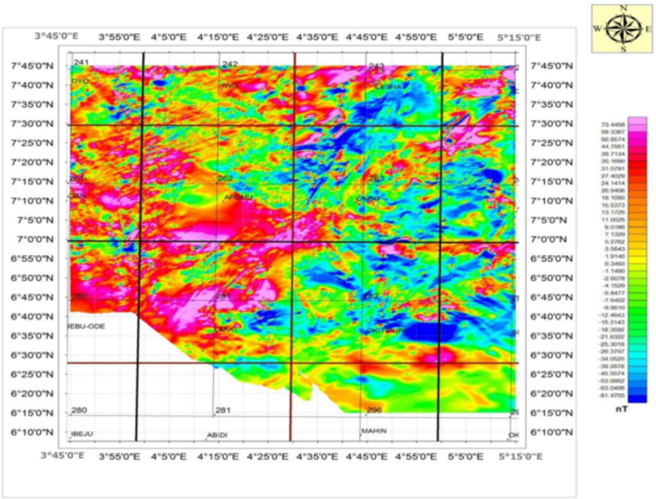

Figure 5. Residual magnetic field intensity map of the study area (a constant TMI value of 33,000 nT has been removed).

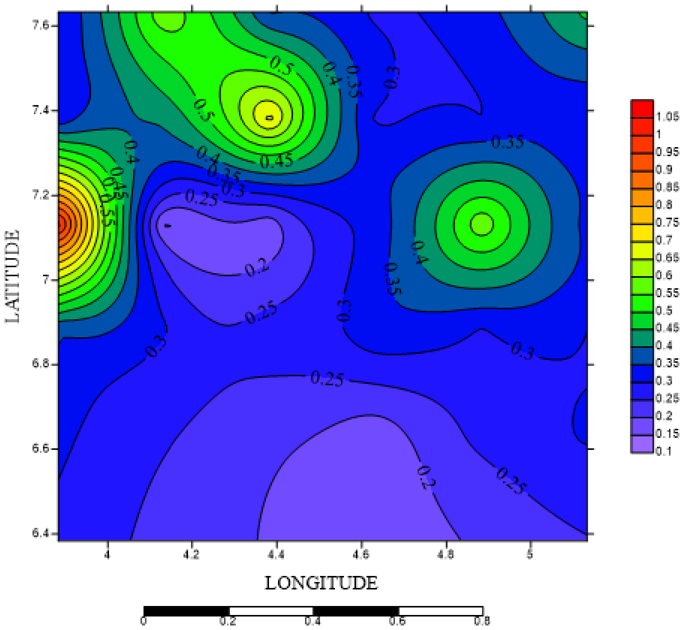

Figure 6. Spectral depth to the top boundary (Z_t) contour map (at 0.05 km interval).

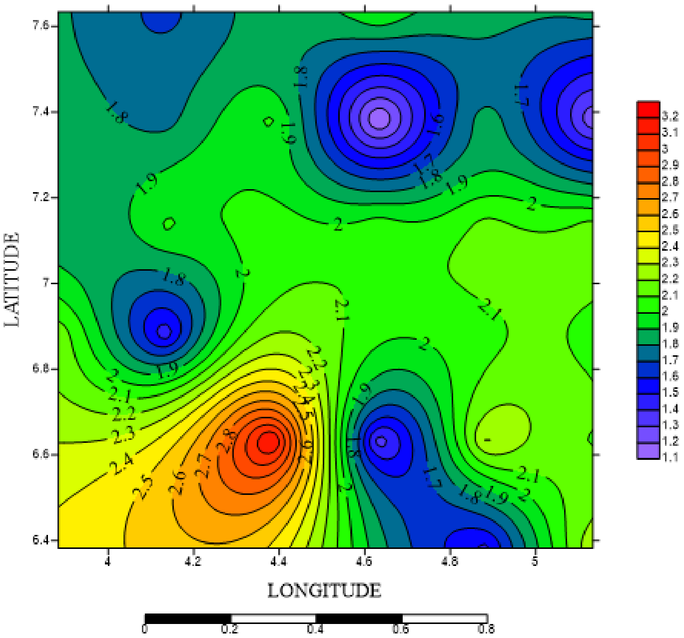

Figure 7. Spectral depth to centroid (Z_o) contour map (at 0.1 km interval).

the centroid (Z_o) contour map (Figure 7), Curie point depth contour map (Figure 8). These are aimed at having a more vivid understanding of the subsurface temperature distribution. In this study, a constant regional value of 33, 000 nT was subtracted from the total magnetic field intensity (Figure 2). The study area showed variabilities in magnetic field intensities. High magnetic field intensity of 122.948 nT was observed around, Oyo (Sheet No. 241), Iwo (Sheet No. 242), Ilesha (Sheet No. 243), Ibadan (Sheet No. 261), Ife (Sheet No. 262), Ijebu-Ode (Sheet No. 280), Lekki-Epe (Sheet No. 281). This could be as a results of the influence of igneous and metamorphic rocks from the rejuvenated Nigerian-Dahomeyan formations. Several other areas on the map such as; (parts) of Ilesha (Sheet No. 243), Ondo (Sheet No. 263), Akure (Sheet No. 264), Okitipupa (Sheet No. 282) and Siluko (Sheet No. 283) recorded negative magnetic anomalies.

4.2. *DISCUSSIONS*

The observed variations in magnetic intensity suggest diversity in magnetic properties of the subsurface rocks. Also, closures of magnetic low indicate areas of thick sedimentary cover which means that the basement in such area is deep whereas closures of magnetic high could either be due to thin sedimentary cover, shallow basement, another magnetic source or basic intrusion into the igneous/metamorphic basement rocks [2]. On the other hand, the residual magnetic map (Figure 5) showed widespread closures, made-up of closely spaced linear sub-parallel orientations, suggesting that faults or local fractures may have passed through these locations. The aforementioned geological trends appear as thin elliptic closures as a results of the oxidation of magnetite into hematite and/or the stuffing of fracture planes by dyke looking bodies having magnetic susceptibilities that contrasts that of the host rocks.

Magnetic survey data are customarily analyzed by evaluating the magnetic source depths [19], such an assessment usually reveals the presence of two types of lower boundaries; the first correlates with vertical changes in the crustal composition, whereas the second is consistent with a substantial increase in temperatures at depth which brings about the loss of the rock's ferromagnetic properties [20]. In this regard, logarithmic plots of the spectral energy versus frequency were performed, from which the magnetic source depths made up of both the spectral depth to top boundary Z_t (Figure 6) and spectral depth to the centroid Z_o (Figure 7) were computed. Depths to the shallow magnetic source Z_t (depth to top boundary) range between 0.14286 km to 1.02632 km. This represents the sediment thickness or depth to the top of the bedrock. Depth to the top of basement is deep-

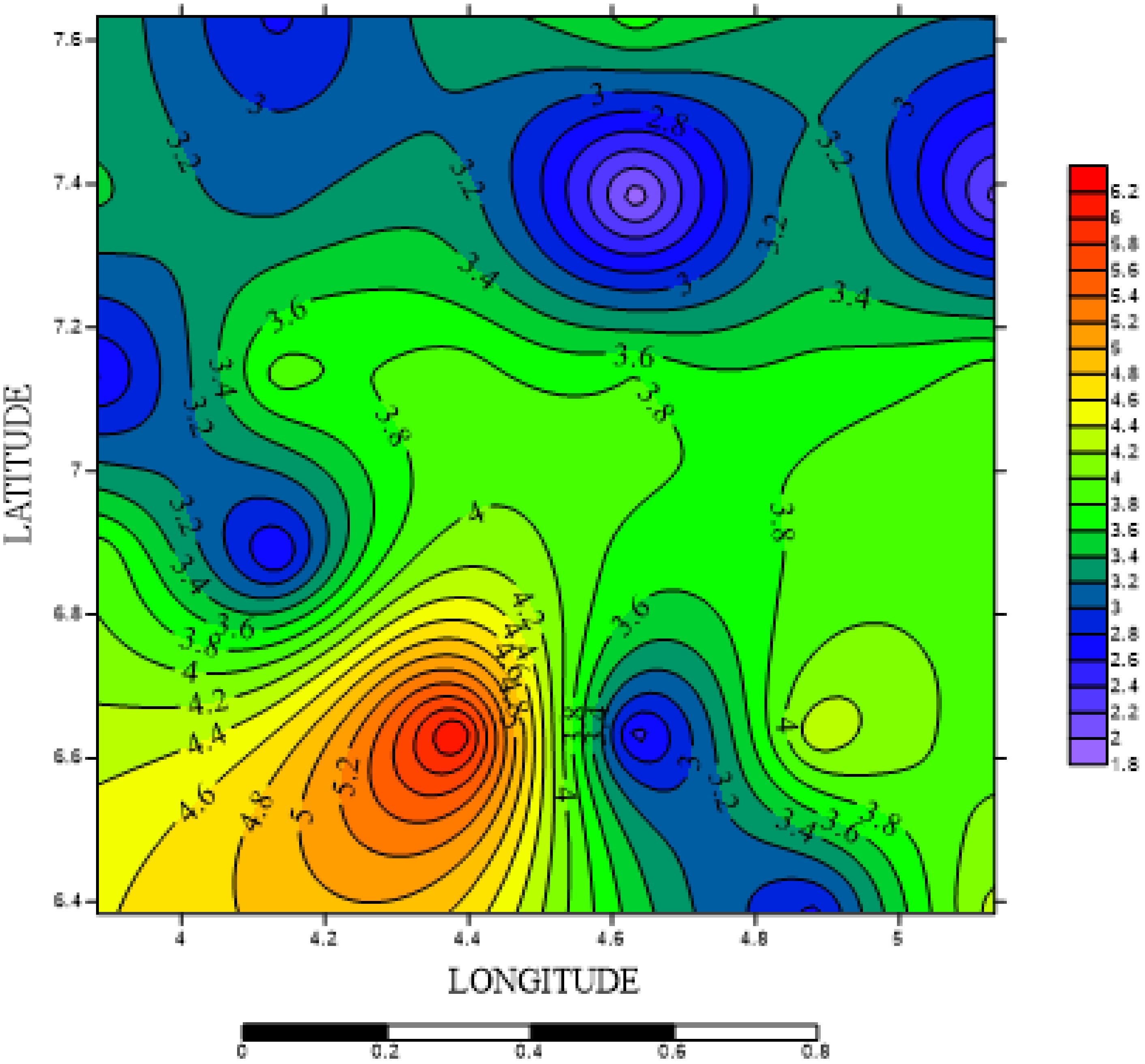

Figure 8. Curie point depth (Z_b) contour map (at 0.2 km interval).

est at the Northwestern part while it is shallower at the central and Southern portion of our study area (Figure 6). However, the spectral depth to the centroid Z_o or deeper magnetic source (Z_o) estimate reveals a largely undulating depth values which varies from 1.08333 km in the North central part to 3.23529 km in the Southwestern part of the study region (Figure 7).

The primary sources of the first layer depth are probably magnetic rocks, or effects of intrusions and outcropping Basement rocks. Whereas, the second layer is considered the intrusion of magnetic rocks into the Basement beneath the sedimentary layer. In some cases, intra Basement features such as fissures and magma intrusions deeper than the bedrock, can also contribute to the depth of the second layer. Also, the computed Curie Point Depth (Z_b) shows that depth to the magnetic source ranges between 1.87380 km and 6.25629 km (Figure 8). It is observed that the magnetic source depth in the Northwestern portion varies between (2.8 – 3.8) km, North-central (2.0 – 3.8) km, Northeastern (2.2 – 3.8) km, Southeastern (2.6 – 4.0) km parts are all generally shallower compared to the Southwestern (3.8 km – 6.3 km) part of the study area. This means that the North-central region is the shallowest, followed by the Northeast, Northwest and then the Southeast.

The shallow Curie point depth is probably attributed to the upwelling of magma, magmatic intrusion at depth in the highly fractured quartzite units and the intruded older granite units. Whereas the deep Curie point (3.8 km – 6.3 km) observed in the Southwestern part is likely because of the isostatic compensation/recovery of the area in question. Results of the spectral depths are consistent with the global model which relies on the premise that sedimentary rocks have rather low magnetic intensity and the observed intensity over the region is mainly from the igneous or metamorphic Basement rocks [21], or in some cases sedimentary rocks with banded iron formations. Therefore, shallow Basement reflects high magnetic intensity while the deep seated basements invariably means thick sediment hence low magnetic intensity [2].

Curie points depth are less than 10 km underground in volcanic and geothermal regions, 15–25 km deep on island arcs and ridges, more than 20 km on plateaus and 30 km deep on trenches, as reported by Tanaka *et al*. [22]. From the results above, it is obvious that the research area is well suited for the first prescription since Curie point depths are generally less than 10 km in depth across the entire study area and thus indicates that the entire study area is an explorable geothermal field, especially the North-central region which harbors the shallowest Curie point depth.

Furthermore, the presence of some geothermal signatures such as waterfalls and warm springs at different locations in the study area coupled with the warm temperatures recorded in them validated the deductions made in this study and hence supports the results obtained. The 70 °C Ikogosi warm spring (Ekiti state), the Erin-Ijesha waterfall (Osun state), the Arinta waterfall (Ekiti state), and the Effon-Alaaye waterfall (Ekiti state) are among the waterfalls and warm springs. Also, the Owu waterfall, Soose spring, Kange spring and Agbonna springs all in Kwara state which are located northwards of our study area, provides additional geothermal signatures. The locations of the above geothermal signatures supports the logic that dense magnetic crust indicates stable continental regions, contrarily, a slim magnetic crust indicates regions of active crustal movement corresponding to shallow Curie point depths [17].

The most crucial factors for the generation of geothermal resources in areas with low curie point depth are the reliability of the heat source and nature of the heat channels. The heat source may be due to the emplacement of igneous rocks, and in a case where the magma is cooled and couldn't support a continuous supply of heat, the deep structure formed by the intrusion of igneous rock becomes a new channel for groundwater and rainwater [23]. Certainly, this research clearly shows that Curie point depth is strongly influenced by the local geology, which is in line with the findings of other studies [4, 6, 17, 20, 24, 25].

5. CONCLUSION

The study area exhibits a mean Curie point depth value of 3.49663 km, with depths to the shallow magnetic source ranging from 0.14286 km to 1.02632 km, and depths to the deeper magnetic sources spanning from 1.08333 km to 3.23529 km. The deeper magnetic sources are likely attributed to the presence of crystalline basement, while the shallower magnetic sources result from near-surface magnetic sources (igneous or metamorphic) that have permeated the sedimentary strata. The overall trend of the spectral depths aligns with the prevailing geothermal and geotectonic features in the study area. Additionally, measurements indicate that Curie point depths are notably low in locations with a substantial degree of geothermal signatures. Consequently, it is acknowledged that regions exhibiting high geothermal activity or signatures correspond to areas with a shallow depth of the Curie point. Areas with low Curie point depth may be linked to intrusion by basic igneous or metamorphic rocks, leading to hydrothermal alteration of the surrounding rocks. Consequently, we recommend the entire study area for subsequent geothermal energy investigations, placing particular emphasis on the North-central region, which has the shallowest Curie point depth.

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