

TECTONIC SETTING ANALYSIS AND GEOTHERMAL ENERGY ESTIMATION RECONNAISSANCE FOR SUSTAINABLE ENERGY DRIVE IN PARTS OF MIDDLE BENUE TROUGH USING AEROMAGNETIC DATA

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ABSTRACT

This study focused on the tectonic setting and geothermal potential for selected areas within the Middle Benue Trough, North-Central Nigeria, using aeromagnetic data. Spectral analysis was employed to estimate the geothermal gradient, heat flow, and Curie point depth (CPD). The spectral analysis was carried out by dividing the upward continuation map to 15km into 36 blocks with overlapping pixels. The depth to the centroid (Zo) and the top (Zt) were estimated from the spectrum of each block. Geothermal gradient, depth to the bottom of the sources, Curie point depth (CPD) and heat flow were calculated using an empirical formula. Lineaments were extracted from aeromagnetic and Landsat imagery data. Tectonically, the lineaments extracted show NE-SW, NNE-SSW, and NW-SE trends, with predominantly a few N-S trending features. From the lineament density map, it can be inferred that lineaments play significant roles in controlling geothermal potential and heat flow in the area. The lineaments identified are mostly related to structures such as joints, fault-outs, dykes, and fissures. The results of the spectral analysis revealed that the depth centroid ranges from 2.73 km to 9.09 km, the depth to the top ranges from 1.11 km to 1.89 km, the Curie point depths range from about 3.79 km to 16.38km, the geothermal gradient ranges from 35.41 to 149.89 °C/km, and heat flow ranges from 88.52 to 382.59 mW/m². The obtained values were within the established global values for geothermal provinces and sedimentary basins. The shallow depths to CPD identified are an indication of high-temperature zones, which may be due to the presence of intrusive rocks. These high heat flow values obtained from the study area are comparable to a heat flow of about 100mWm⁻² which is a good indicator for harnessing geothermal energy. Using the empirical relations of depth to CPD as a function of depth, a geothermal gradient of 3 °C/100m or 30OC/Km. With an average thermal conductivity of about 105.68 to 227.63mWm-2, the area has great potential for geothermal energy, which is the most crucial and important finding of this study.

Keywords: Geothermal, Energy, Aeromagnetic, Depth, Centroid, Data.

INTRODUCTION

Nigeria's energy crisis is not likely to be solved in the foreseeable future despite the nation's abundance in solar, hydrological, radioactive mineral, and geothermal energy resources. Since geothermal energy is a clean, virtually inexhaustible supply with lower greenhouse gas emissions than traditional hydrocarbon-based power production, the transition from hydrocarbons to

geothermal energy might be the most environmentally advantageous option (Elbarbary et al., 2022). With petroleum and other hydrocarbon commodities becoming more expensive and the strong desire to mitigate the consequences of climate change, the need for African countries to develop new strategies for meeting their energy needs has become more pressing than ever. Consequently, geothermally viable regions in Nigeria can provide the continent with much-needed energy resources. Geothermal energy, if properly explored and harnessed by African countries, will significantly contribute to the countries' ability to achieve energy independence and solve problems of epileptic power supply. There are several stages that must be completed before any geothermal project can start. Exploration is a set of procedures including geological field mapping (fundamental geology and the study of structures), in situ geothermal measurements, including pH, temperature, and hydrochemistry analysis of productive fluids, geophysical investigations such as gravity, magnetics, and magnetotellurics; and Numerical quantitative modeling (Elbarbary et al., 2022).

The economy of East Africa is currently tapping into geothermal energy sources for electricity generation worth 630 MW per annum. Kenya emerges as the African leader in harnessing geothermal energy, with 40% of its electricity production from the resource, leaving Nigeria with no geothermal power plant currently. Kenya started investigating geothermal power in the late 1970s and has made considerable progress in its exploitation and utilization, placing Kenya among the top ten geothermal countries worldwide according to the Geothermal Council Resource (Elbarbary et al., 2022). Nigeria will continue to experience energy challenges as the giant of Africa if the exploitation of its geothermal energy potential is not prioritized.

Geothermal energy refers to the heat produced within the earth's crust. This heat is brought to the surface of the earth by water and/or steam to provide energy. Depending on the properties of the fluids, geothermal energy can be employed for heating and cooling applications or electricity generation. For electricity generation, resources that operate at high or medium temperatures are required and are predominantly found near tectonic plate boundaries, as indicated by geophysical studies (Aigbedion et al., 2022).

Heat derived and stored within the Earth may come from the creation of the Earth and subsequent decay of uranium, thorium, potassium, and other radioactive elements in the Earth's rocks (Downing & Gray, 1986). The upwelling of magma to the surface during rifting events is frequently linked to a variety of geodynamic

processes, including tectonic lineament outcropping and geothermal power production (Komolafe, 2010). Discontinuities in the lithosphere are primarily associated with the structural geology of the study area. Tectonic lineaments and surface thermal structures such as faults and fractures are essential to any investigation of the structural evolution and geothermal characteristics of the region.

The continuous buildup of stress along discontinuities can facilitate fluid flow and play a key role in the genesis of geothermal provinces (Komolafe, 2010). Hence, the exploitation of geothermal resources in Nigeria has the potential to satisfy the energy needs of an emerging industrialized country (Obande et al., 2013). Nigeria is among the African nations that possess

Nigeria stands as one of the countries in Africa with potential for geothermal energy (International Geothermal Association, IGA, 2020). Surface indications of geothermal anomalies such as springs alongside lava flows have been documented within the Precambrian Basement Complex rocks and sedimentary basins of Nigeria (EL-Qady, 2006; Yohanna et al., 2023; Kana et al., 2021; Sha et al., 2015; Chababaane et al., 2017; Lucky et al., 2026; Azaiez et al., 2020; and Okiyi et al., 2021).

Geophysical surveys consist of direct and indirect methods that involve measurement of data to directly infer information about the chemical and physical properties associated with the targeted areas under investigation. The direct method includes measurements of fluid content, pH, temperature, etc. Conductivity and resistivity data are obtained from geothermal manifestations shaped by geothermal processes, including electrical resistivity, thermal conductivity and magnetotelluric techniques. On the other hand, indirect methods involve the collection of data about the physical parameters of the rocks hosting a geothermal reservoir to indirectly estimate the targeted variables. Examples of such methods are the measurement of magnetic properties and density. Seismic velocity is useful in generating geophysical data about the lithologic variations in the studied area (Sha et al., 2015; Chababaane et al., 2017; Azaiez et al., 2020; Okiyi et al., 2021; and Georgsson, 2021). Various geoscientific techniques have been employed in the exploration of geothermal energy worldwide. For instance, in Mexico, geothermal fields in Los Azufres were evaluated using a geographic information system (GIS) by combining geological and geophysical data during the exploration process (Prol-Ledesma, 2020). A GIS-based model has been created to explore the geothermal potential in West Java, Indonesia (Carranza et al., 2008). In Japan, a GIS-based weighted overlay model was employed to develop a geothermal positivity map for the regions of Iwate and Akita in Northern Japan by considering the geologically, thermally and geochemically favorable regions (Noorollahi et al., 2007). In Turkey, the weighted overlay technique was employed to create a map illustrating the geothermal favorability of Western Anatolia by employing earthquake epicenter and geothermal databases; thematic layers of magnetic anomalies and tectonic lineaments provide significant insights (Tüfekci et al., 2010). In Turkey, within the Akarcay Basin, a GIS-based Minor Civil Division method was utilized, incorporating thematic inputs such as surface temperature, density, proximity to existing geothermal geological fields, faults and geothermal manifestations (Yalcin & Gul, 2017). A GIS-based data integration tool was utilized in Italy to create a geothermal favorability map for Sicily, located in southern Italy (Trumpy et al., 2015). A GIS-based weighted overlay method was employed to create a geothermal

favorability map in Egypt, utilizing various inputs such as tectonic lineament information, temperature databases, and geophysical potential field data (Abdel Zaher et al., 2018; Abuzied et al., 2020; Abdel-Fattah et al., 2021). Yohanna et al., 2023, and Lucky et al., 2026 utilized spectral analysis to estimate geothermal energy potential in Mambilla Plateau and the Yola arm of the Gongola Basin. Most of the studies did not utilize the upward continuation map of the areas for the spectral analysis.

This study investigates the potential of geothermal energy in parts of the Middle Benue Trough using structural and aeromagnetic data for sustainable energy development. This study will contribute to future geothermal investigation studies that focus on targeting specific areas with high potential. The distinctiveness and originality of this study are that it integrates both structural studies and aeromagnetic data using spectral analysis on an upward continuation map of the area to investigate the geothermal potential in the area, instead of the traditional and expensive borehole data and GIS-based models. In addition, the method used in the study is flexible to accommodate anticipated adjustments by incorporating new geoscientific data as they emerge and implementing simple reclassification to generate potentiality maps for any given location in the country. Selection of a suitable site for the exploitation of geothermal resources is undoubtedly not easy; it is difficult, and various factors need to be taken into consideration. This study provides a suitable guide for site suitability assessment based on energy needs for sustainable development.

MATERIALS AND METHODS

Location, Accessibility and Geomorphology of the Area

The research area is situated within the Awe and Keana Local Government Areas (LGAs) of Nasarawa State. The region is situated at latitudes 8°00'00"N to 8°30'00"N and longitudes 9°00'00"E to 9°30'00"E. The land area covered is 3085.8025 km². The area can be reached via the Lafia – Awe-Keana Road as well as the Lafia - Azara Road. However, the main study area is traversed by footpaths and bushes. The main notable areas are: Akiri, Kanje and Awe. The area has varied landforms which include hills, valleys, as well as stream channels (Figure 1).

Geology and Tectonic Settings of the Study Area

Geologically, the area is under the Central Benue Trough. The trough is characterized by Cretaceous - Recent sedimentary facies such as the Awe Formation, Keana Transitional Formation, and Kanje Siltstone, and recent alluvial deposits. Other outcrops include the Tertiary intrusives of the basic plugs which occur along the extreme west, central and south-western parts of the research region (Figure 2). The Awe Formation is composed of finely layered, laminated, pinkish sandstone, mudstone and siltstone (Kaura et al., 2024). These sandstones, in places, take a paler yellowish hue and occur as coarse feldspathic sandstones with intercalation of shale and crystalline/shaly limestone. The Keana Formation takes a more homogeneous and massive form and is mainly composed of pebbly sandstone beds that are fine to coarse in nature. It seems to be unconformable over the Awe Formation. Brines in the area seem to originate from the shaly interbedded rocks and more permeable sandstone (Offodile, 2002). The Keana, Awe, and Kanje siltstones appear to pass into black fissile shale rocks. Shaly black rocks grade to micaceous, arkosic sandstone beds that are poorly sorted, which are sometimes interbedded with

mudstones and have characteristics of planar cross-bedding. The partially developed anticline within Awe suggests lithology with a dip range of 17-32° to the north and south before becoming progressively shallower to the northeast, reaching only 3-9° in that direction. The region is primarily characterized by longitudinal strike-slip faults that run parallel to the main fold axis. This implies it has already undergone extensive plate tectonic adjustments within the area; in fact, an anticline has been faulted (Aigbedion et al., 2022).

Climate and Vegetation of the Study Area

The study area falls under the tropical savannah climatic regime with two separate seasons: one characterized by wet conditions and the other by dry conditions. The rainy period occurs between

April and October, while the dry period occurs between December and February (Iloeje, 1981). The rain, which starts in April, leads to a marked decrease in temperature in the study area. This continues until the end of the rainy season in October, after which another decrease in temperature occurs in November/December when the Harmattan winds start blowing. The temperature records in the study area range from 15.6°C to 26.7°C, with an annual rainfall range from 1317 mm to 1450 mm, while the average annual rainfall is 1107.2 (Iloeje, 1981). The area is under the Savannah region of Nigeria, and, like many other parts of the belt, it comprises open mature sub-humid woodland and tall grasses. However, the vegetation cover has been largely affected by human activities such as overgrazing, bush burning, cutting of trees for timber, and farming activities (Iloeje, 1981).

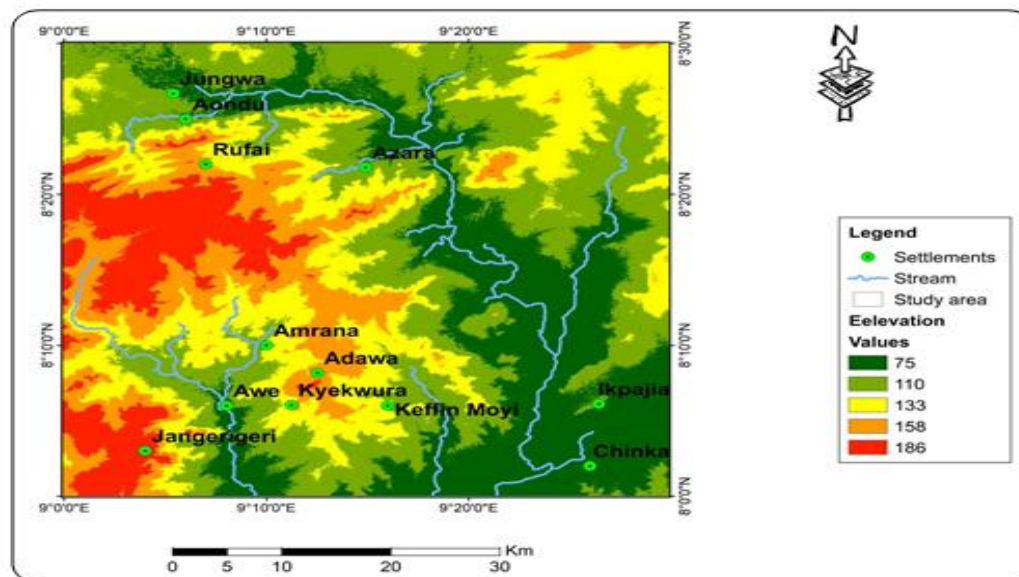


Figure 1: Digital Elevation Map of the Study Area

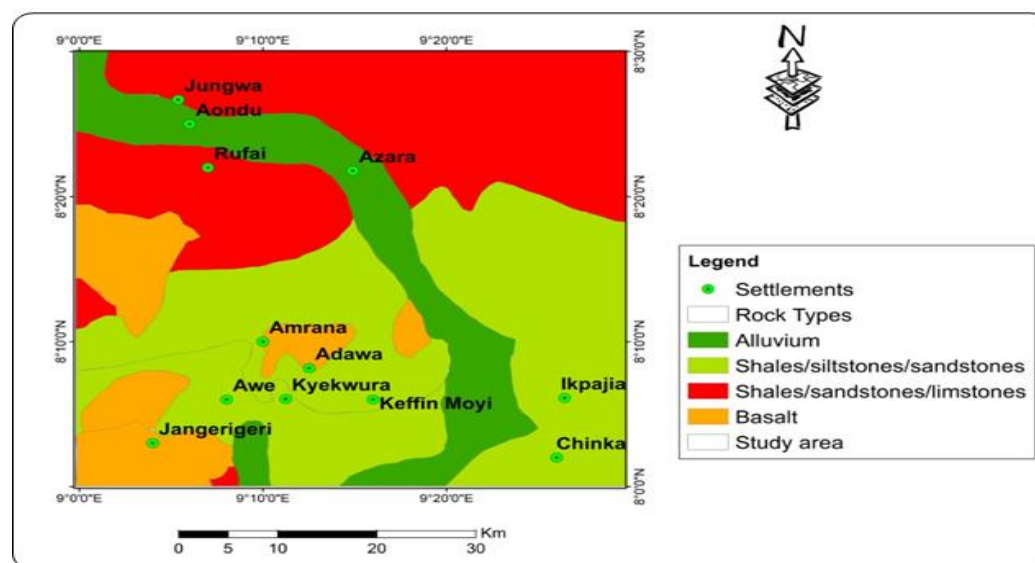


Figure 2: Geological Map of Akiri and Environs

Aeromagnetic Dataset

A high-resolution Akiri Sheet 232 aeromagnetic dataset was utilized for this study. The data obtained from the Abuja office of the Geological Survey Agency of Nigeria were acquired by Fugro Airborne Limited Surveys. Typically, these datasets feature a flight line spacing of 500 meters and a terrain clearance ranging from 80 to 100 meters, which offers a high spatial resolution suitable for in-depth subsurface investigations (Reeves, 2005). The initial data processing involved standard corrections, the removal of the International Geomagnetic Reference Field (IGRF), and levelling. Additionally, micro-levelling was performed to eliminate line-based noise and to guarantee data consistency (Minty, 1997; Oladunjoye et al., 2016; Patterson & Reeves, 1985). Since it is a low magnetic latitude area, the Reduce to the Magnetic Equator (RTE) filter was utilized to accurately align magnetic anomalies with their respective sources (Blakely, 1996; Telford et al., 1990). By subjecting the reduced-to-equator map to first, second, and tilt angle derivatives, the structural boundaries were outlined. The residual map was also upward continued to about 15km and segmented into overlapping spectral windows to minimize edge effects during analysis (Spector & Grant, 1970). The slopes of the logarithmic power spectrum were utilized to ascertain the depth of the Curie point (Z_b).

$$Z_b = 2Z_0 - Z_t \quad (1)$$

In accordance with the work of Tanaka et al. (1999), the geothermal gradient (dT/dz) was estimated based on a Curie temperature of 580 °C, while heat flow (Q) was determined utilizing Fourier's law:

$$Q = \lambda \left(\frac{dT}{dz} \right) = \lambda \left(\frac{580^\circ\text{C}}{Z_b} \right) \quad (2)$$

Here, λ denotes thermal conductivity, which is typically regarded as 2.5 W/m°C for crustal rocks (Turcotte & Schubert, 2002; Ruban, 2015; and Tanaka et al., 1999).

RESULTS AND DISCUSSION

Results

The Total Magnetic Intensity (TMI) map of the area (Figure 3) was subjected to regional residual separation to derive the regional field and residual field (Figures 4 and 5). The residual magnetic field map was also reduced to the magnetic equator to position anomalies directly over their sources (Figure 6). To calculate the total for the Z-column, it was necessary to perform a straightforward arithmetic addition of 33,000 nT to each value in the Z column after acquiring the data from NGS, as this step was essential before any further processing could be considered valid. The Universal Transverse Mercator (UTM) projection technique was employed for georeferencing, with X and Y identified as optimal columns. The data gridding procedure ultimately generated a grid that depicted the aeromagnetic total field strength through color images. The categorization of the structural features is based on the asymmetrical patterns along NE-SW, NNE-SSW, NW-SE, and N-S directions. The gridded data for the total magnetic intensity map have values of 32949.7304 to 33108.3074 nT, while that of the regional field ranges from 330.5366 to 33387.5372 nT, with the crustal field having values of -390.355 to -241.4547 nT, with a deviation from the mean of -66.5. The reduced to the equator has values of -262.4904 to -252.1535 nT. Computed geomagnetic inclination and declination vary from -8.3° to -7.0° (average: -7.5°) and -2.2° to -2.0° (average: -3.1°), respectively. The region is situated in a zone of low magnetic latitude. The TMI map is composed of high, low, and intermediate magnetic signals that can be linked to rock susceptibility, the depth of the magnetic rock source, the degree of strike, and remnant magnetism (Likkason, 2014).

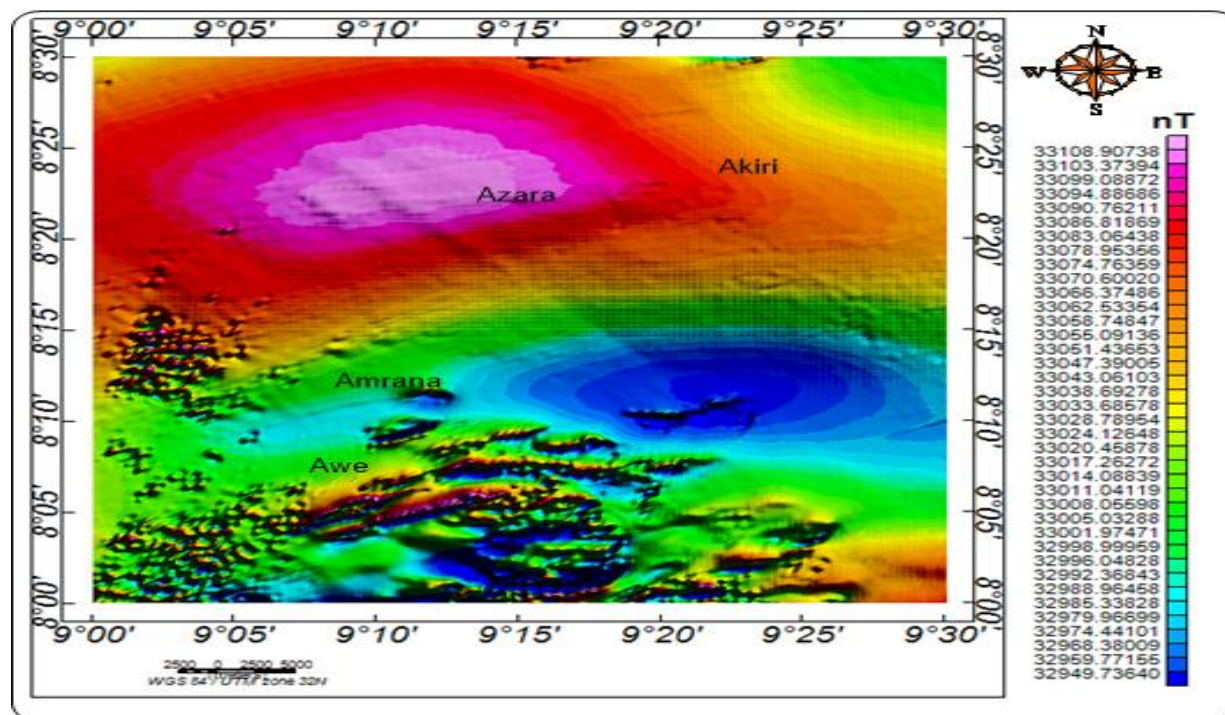


Figure 3: Total Magnetic Intensity Anomaly Map of Akiri and Environs

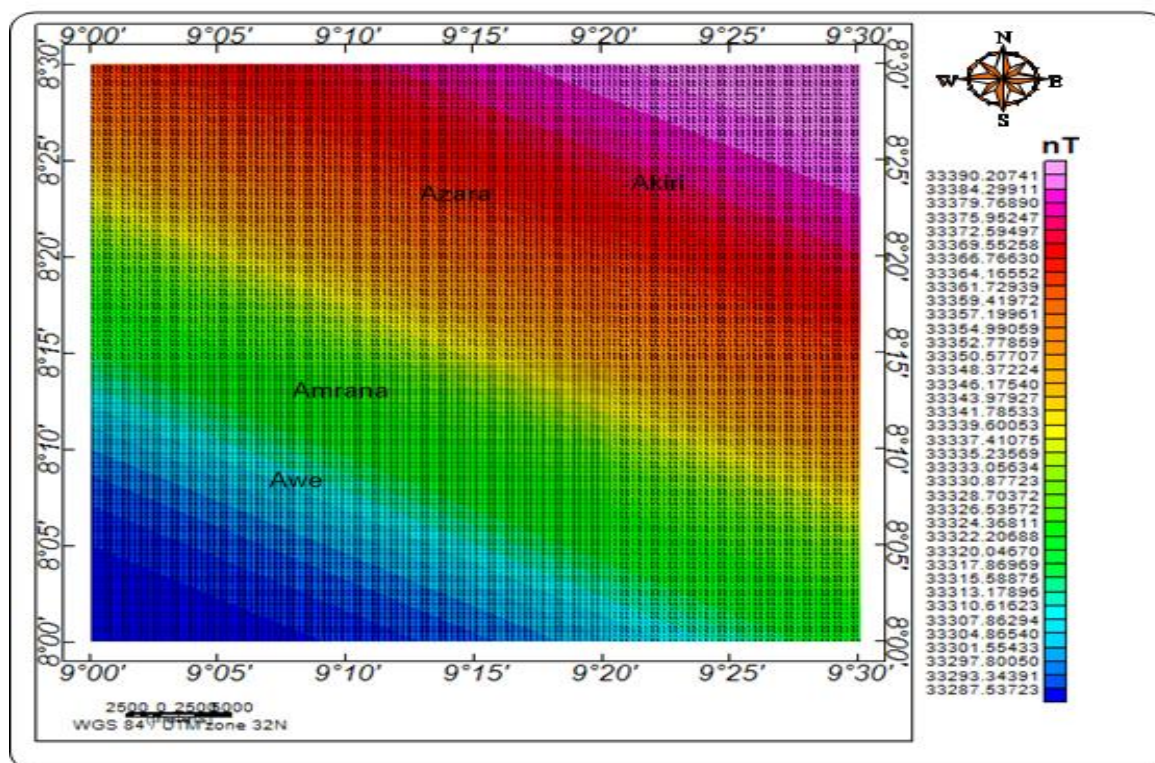


Figure 4: Main Magnetic Field Anomaly Map of Akiri and Environs

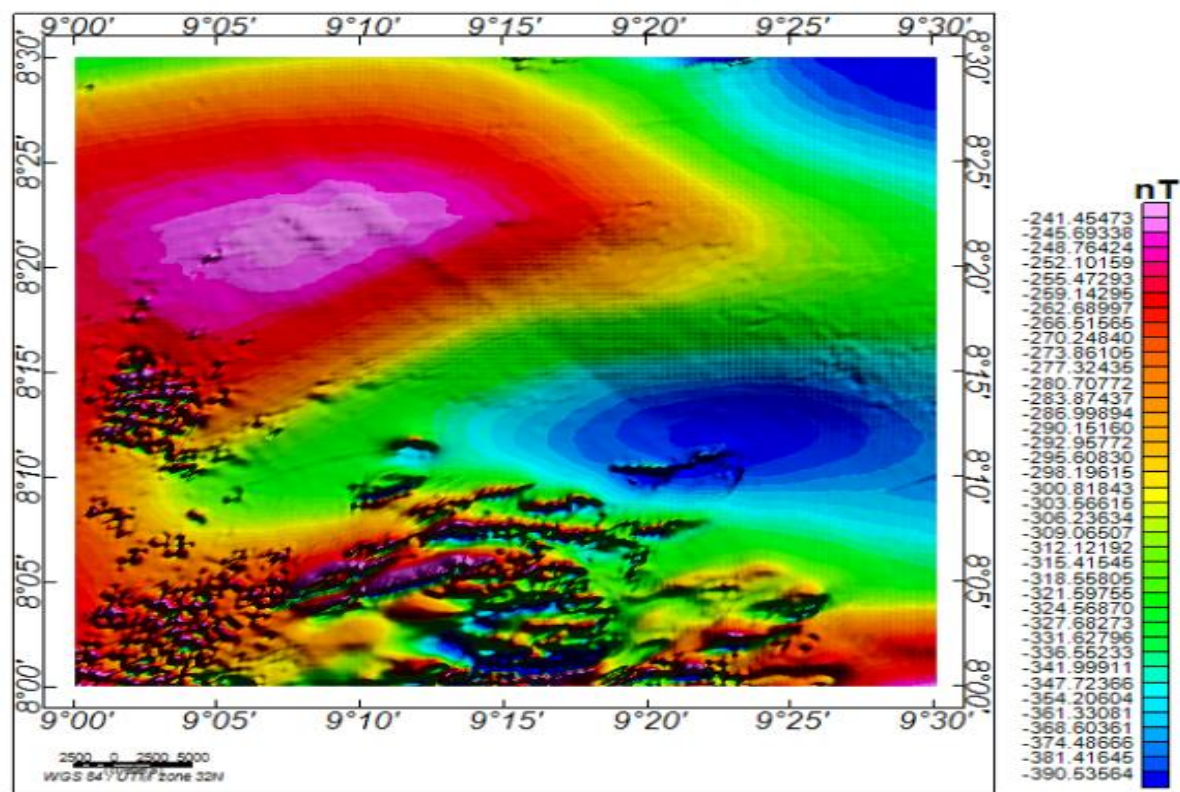


Figure 5: Residual Magnetic Anomaly Map of Akiri and Environs

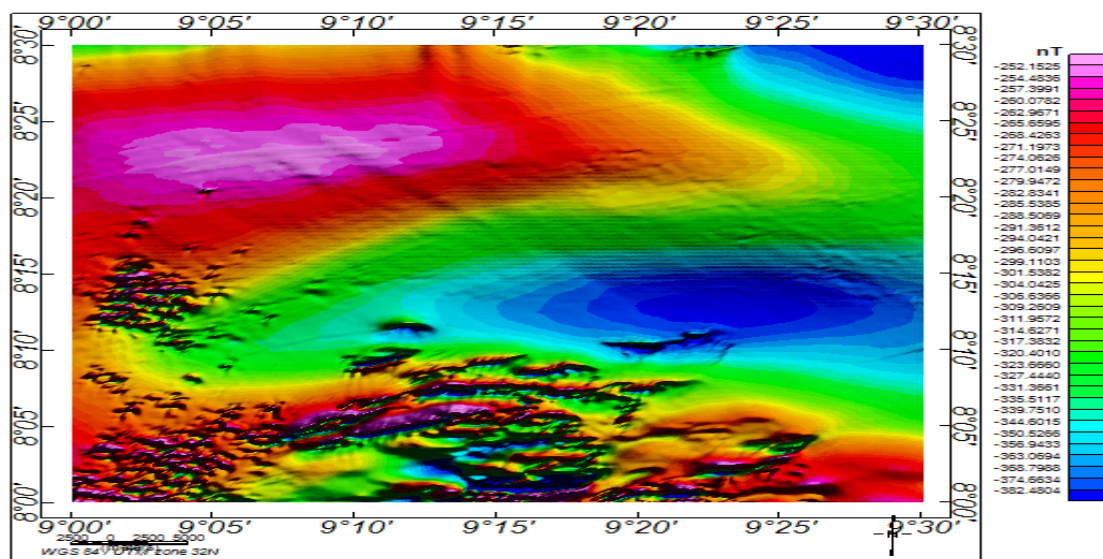


Figure 6: Reduced-to-the-Equator Anomaly Map of Akiri and Environs

Structural Measurement and Lithological Characterization from Aeromagnetic and Landsat Imagery Data

The RTE map grid was processed using first, second, and tilt angle derivative filters to recognize geological bodies such as faults, joints, and lithological contacts, and to enhance weak and strong magnetic anomalies in the area (Figures 7, 8 and 9). Identifying the sudden lateral changes in rock magnetism can facilitate the delineation of contact boundaries between adjacent rocks and intrusions in the area (Nurdiyanto et al., 2004). Lithological contact boundaries in the area serve as a representation of the distribution patterns of signals. The surface and subsurface horizontal contacts of the intrusion are displayed on the derivative maps. There is strong agreement between all the patterns based on the maps. Lineaments were derived from aeromagnetic (Figure 10 and Landsat imagery (Figure 11) data. Lineaments from aeromagnetic

data were processed using the Centre of Exploration Target (CET) in Oasis Montaj software to map lineaments, lineament density zones and lithological boundaries.

Lineaments from the aeromagnetic map are dominant in the southern, eastern, northern and central parts of the area, while those from the Landsat imagery for mapping shallow structures are randomly dispersed in the area and dominantly in the locations of springs (Figure 12). There is a positive correlation between areas of high lineament density and geothermal energy (Andarawus et al., 2023). Key manifestations of geothermal energy include joints, faults, geysers, springs, etc. Structural features greatly influence fluid migration, thereby contributing to geothermal energy. Combining lithological and structural information can help identify targeted geothermal potential zones for energy resource assessment.

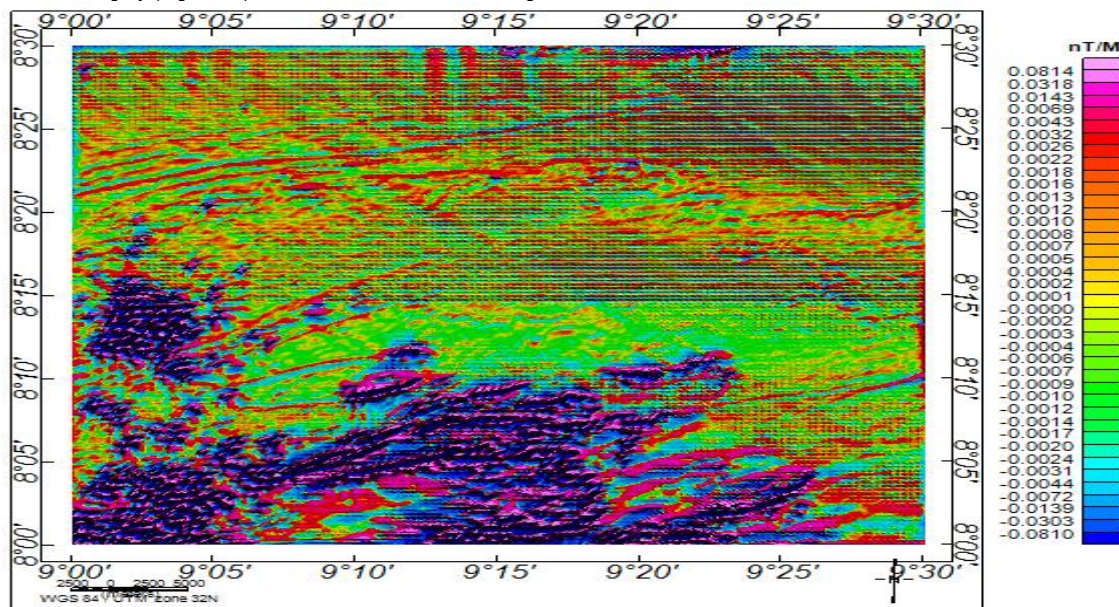


Figure 7: First Vertical Derivative Anomaly Map of Akiri and Environs

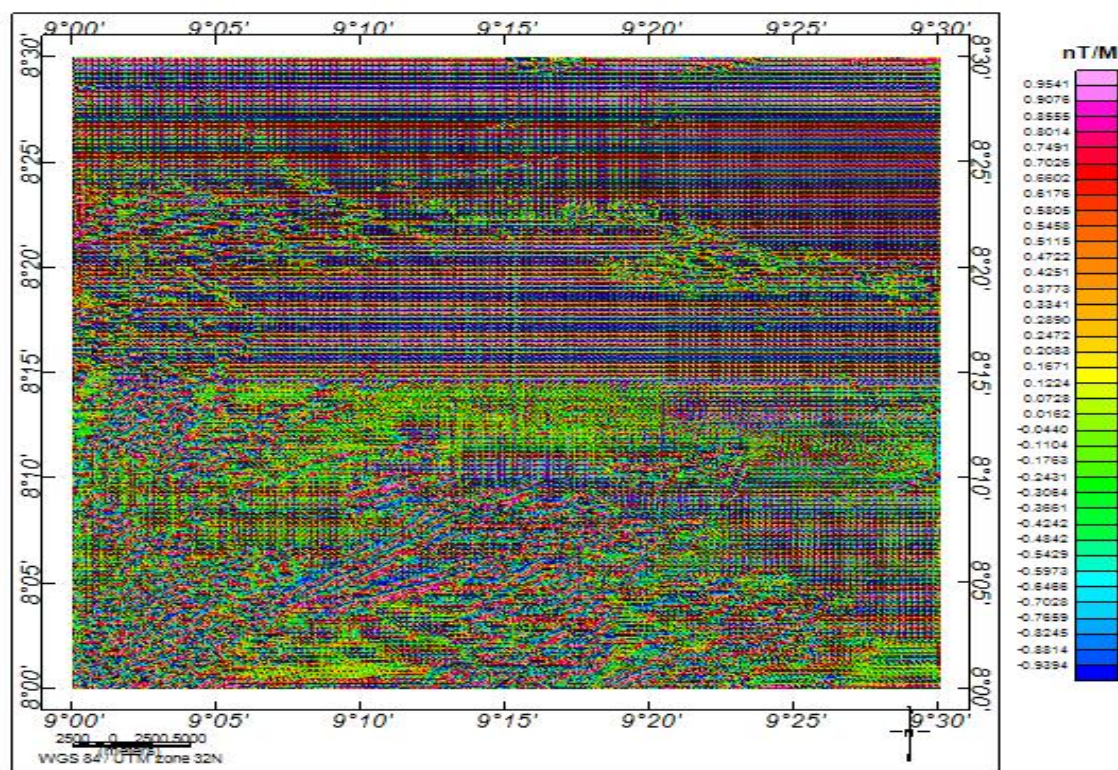


Figure 8. Second Vertical Derivative Anomaly Map of Akiri and Environs

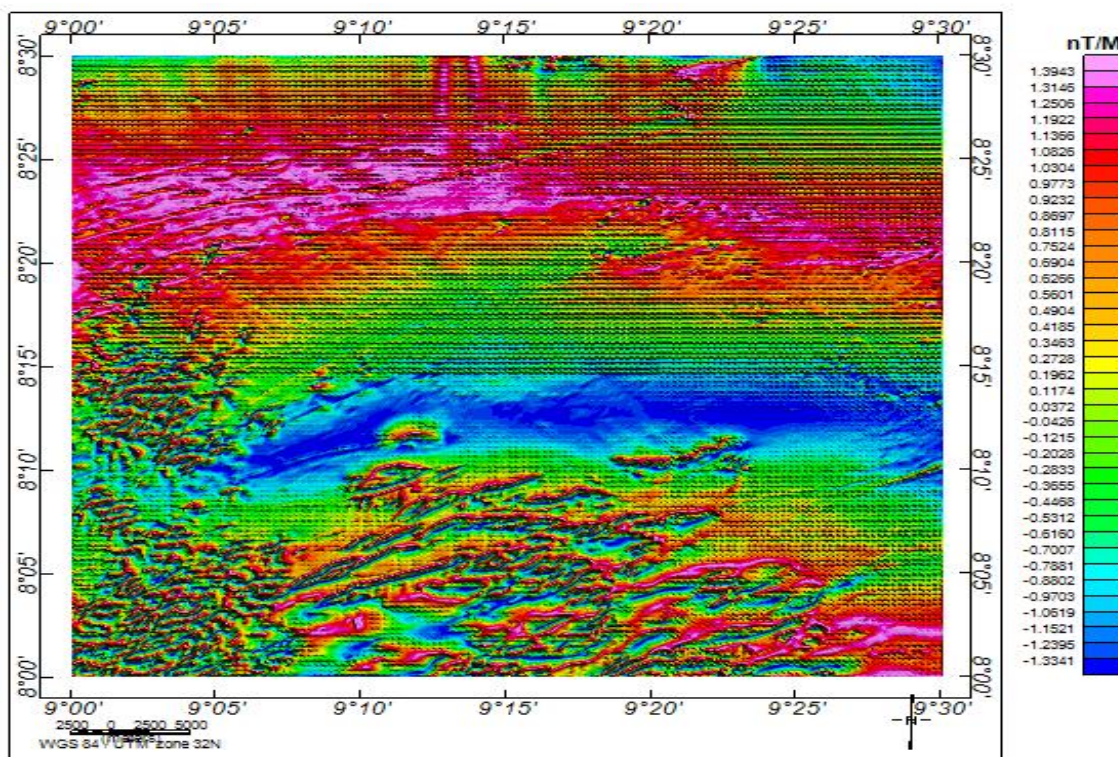


Figure 9: Tilt Angle Derivative Anomaly Map of Akiri and Environs

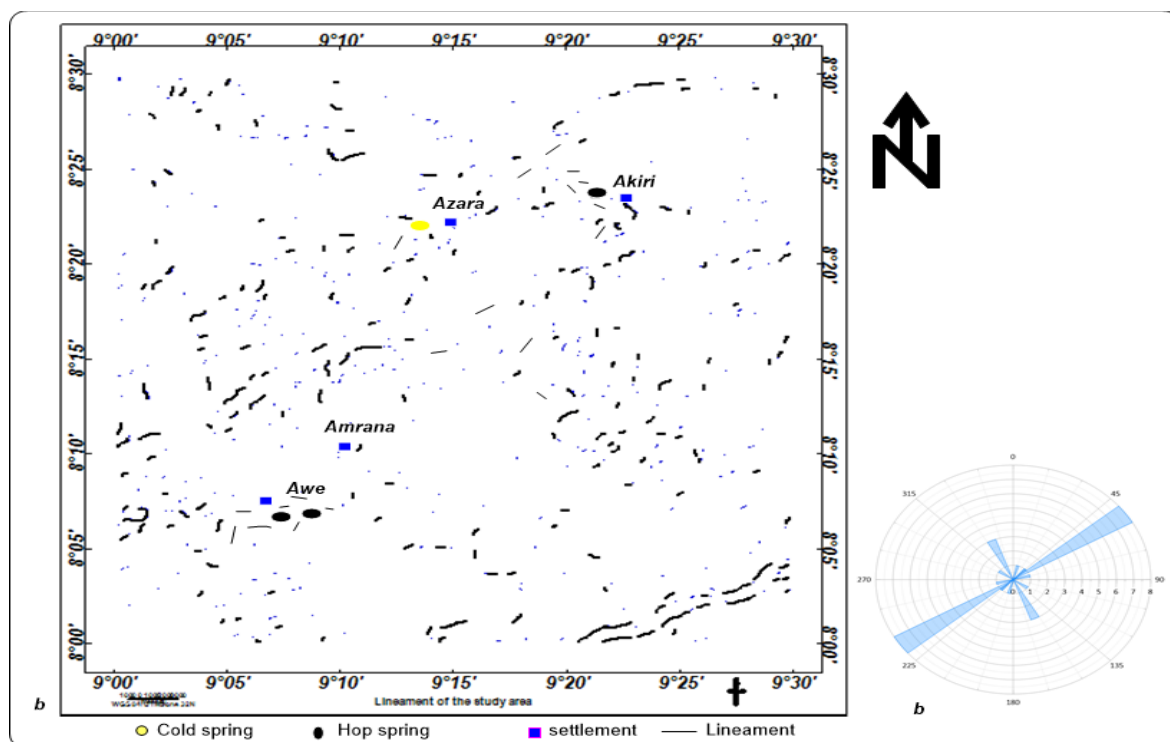


Figure 10: Lineaments extracted from Landsat Imagery Data and (b). Rose Diagram Showing the Tectonic Trends within Akiri and Environs

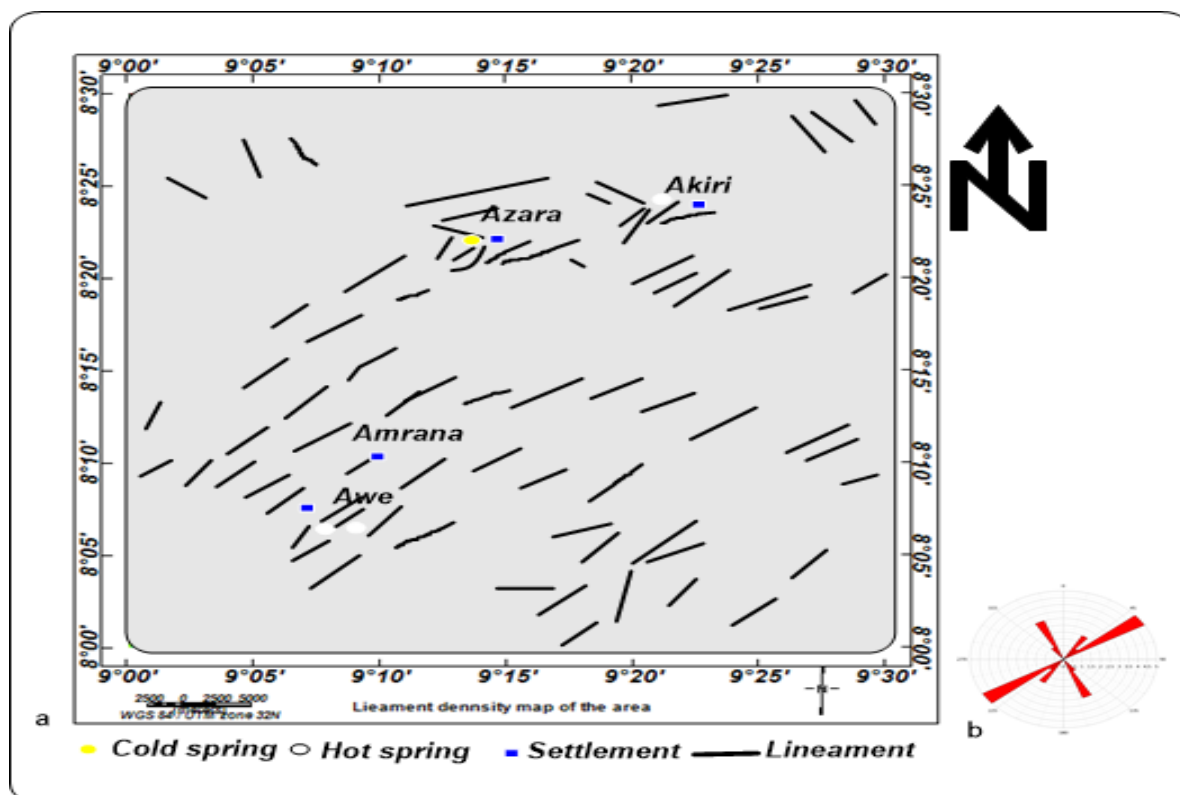


Figure 11: (a) Lineaments extracted from Aeromagnetic Data and (b) Rose Diagram showing the Tectonic Trends within Akiri and Environs

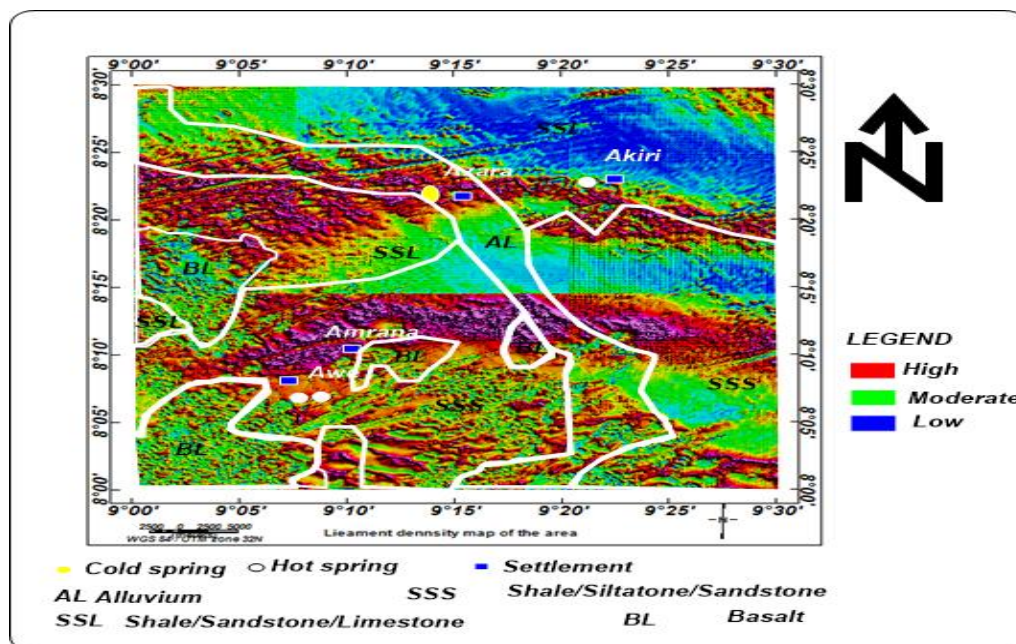


Figure 12: Lineament Density Map and Locations of Springs within Akiri and Environs

Geothermal Gradient, Depth to Centroid, Depth to Top, Curie Point Depth and Heat Flow over the Study Area and Environs

Upward continuation was carried out to effectively enhance short-wavelength anomalies, thereby bringing deeper magnetic sources into sharper focus. The upward continuation map was divided into 36 intersecting square spectral segments to guarantee ongoing spatial coverage and minimize edge-related artifacts during the analysis (Figure 13). For each segment, spectral energy curves were produced and presented as the natural logarithm of energy

plotted against frequency (Figure 14). The computed values for CPD, geothermal gradient, depth to centroid, depth to top, geothermal gradient and heat flow for each block are presented in Table 1. Results from spectral analysis show depth to centroid ranges from 2.73 to 9.09 km (Figure 15), depth to top ranges from 1.11 to 1.89 km (Figure 16), Curie point depths range from approximately 3.79 km to 16.38 km (Figure 17), and geothermal gradients range from 35.41 to 149.89 °C/km (Figure 18). Heat flow in the area ranges from 88.52 to 382.59 mW/m² (Figure 19).

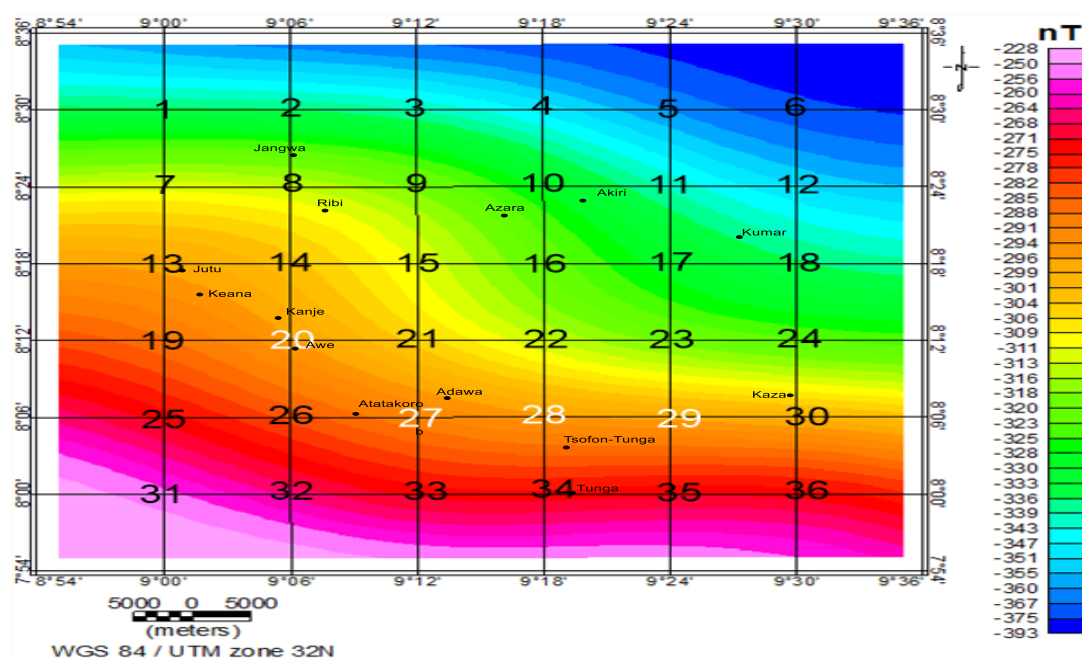


Figure 13: Upward Continuation Map (to 15 Km) in Akiri and Environs

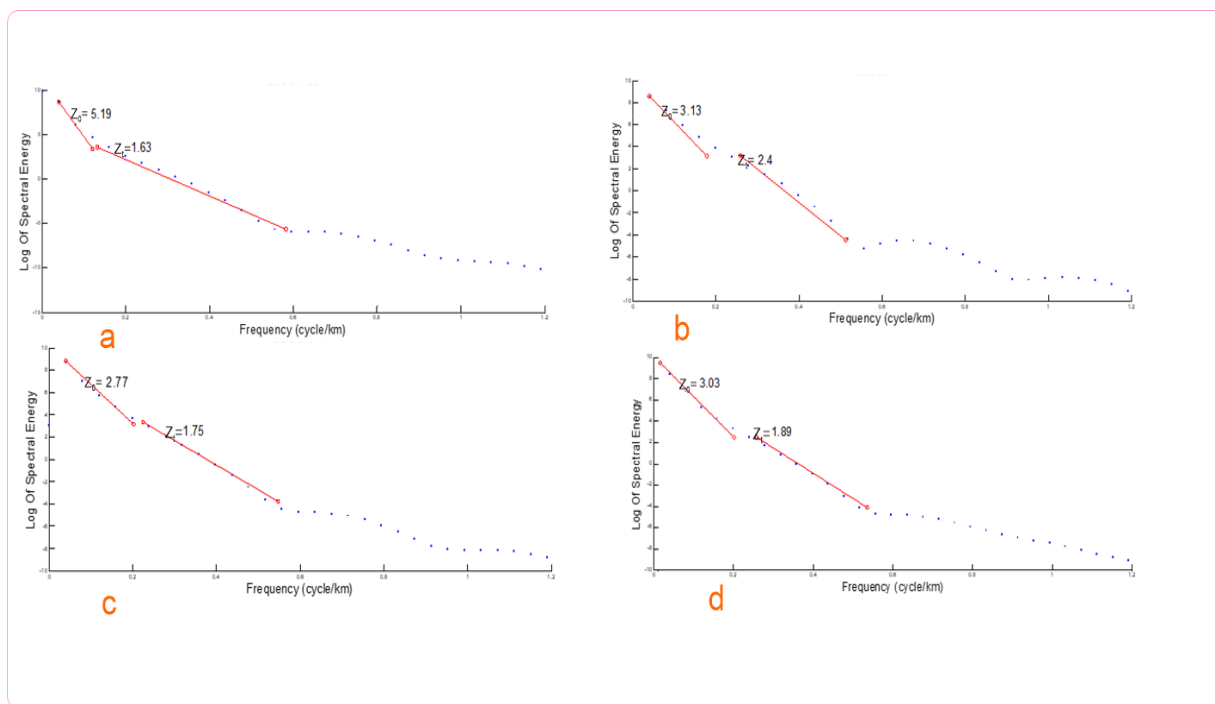


Figure 14: Spectral Plots of Akiri and Environs

Table 1. Estimated CPD, Geothermal Gradients and Heat Flow over Akiri and Environs, part of the Middle Benue Trough

Block	Longitude	Latitude	Depth to the top Z_t (km)	Depth to the centroid Z_0 (km)	Curie Point depth Z_b (km)	Geothermal gradient $^{\circ}\text{Ckm}^{-1}$	Heat flow mWm^{-2}
1	9	8.5	1.23	3.3	5.37	108.01	270.02
2	9.1	8.5	1.2	6.98	12.76	45.45	113.64
3	9.2	8.5	1.58	4.6	7.62	76.12	190.29
4	9.3	8.5	1.44	3.58	5.72	101.4	253.5
5	9.4	8.5	1.49	2.93	4.37	132.72	331.81
6	9.5	8.5	1.82	3.42	5.02	115.54	288.84
7	9	8.4	1.26	5.32	9.38	61.83	154.58
8	9.1	8.4	1.82	5.89	9.96	58.23	145.58
9	9.2	8.4	1.38	7.17	12.96	44.75	111.88
10	9.3	8.4	1.44	8.91	16.38	35.41	88.52
11	9.4	8.4	1.84	4.19	6.54	88.69	221.71
12	9.5	8.4	1.86	6.06	10.26	56.53	141.33
13	9	8.3	1.73	3.11	4.49	129.18	322.94
14	9.1	8.3	1.89	3.03	4.17	139.09	347.72
15	9.2	8.3	1.28	4.49	7.7	75.32	188.31
16	9.3	8.3	1.75	2.77	3.79	153.03	382.59
17	9.4	8.3	2.4	3.13	3.86	150.26	375.65
18	9.5	8.3	2.16	3.33	4.5	128.89	322.22
19	9	8.2	2.15	3.48	4.81	120.58	301.46
20	9.1	8.2	1.67	3.78	5.89	98.47	246.18

21	9.2	8.2	1.63	5.23	8.83	65.69	164.21
22	9.3	8.2	1.63	5.19	8.75	66.29	165.71
23	9.4	8.2	1.97	9.09	16.21	35.78	89.45
24	9.5	8.2	1.23	6.06	10.89	53.26	133.15
25	9	8.1	1.64	3.31	4.98	116.47	291.16
26	9.1	8.1	1.4	4.87	8.34	69.54	173.86
27	9.2	8.1	1.77	3.69	5.61	103.39	258.47
28	9.3	8.1	1.59	2.73	3.87	149.87	374.68
29	9.4	8.1	1.66	3.22	4.78	121.34	303.35
30	9.5	8.1	1.4	4.71	8.02	72.32	180.8
31	9	8	1.44	3.14	4.84	119.83	299.59
32	9.1	8	1.38	5.97	10.56	54.92	137.31
33	9.2	8	1.54	6.01	10.48	55.34	138.36
34	9.3	8	1.5	3.1	4.7	123.4	308.51
35	9.4	8	1.11	2.83	4.55	127.47	318.68
36	9.5	8	1.65	5.23	8.81	65.83	164.59

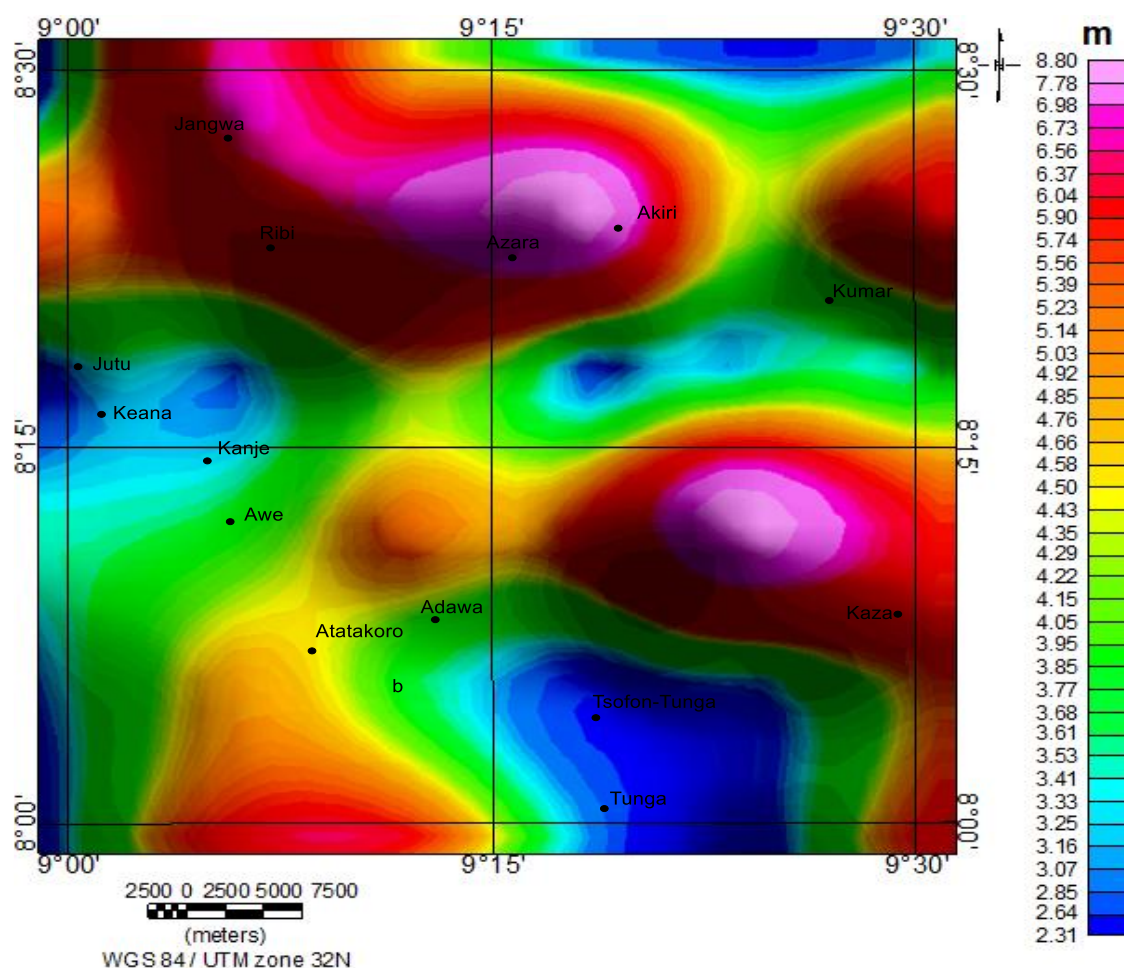


Figure 15: Depth to Centroid Map of Akiri and Environs

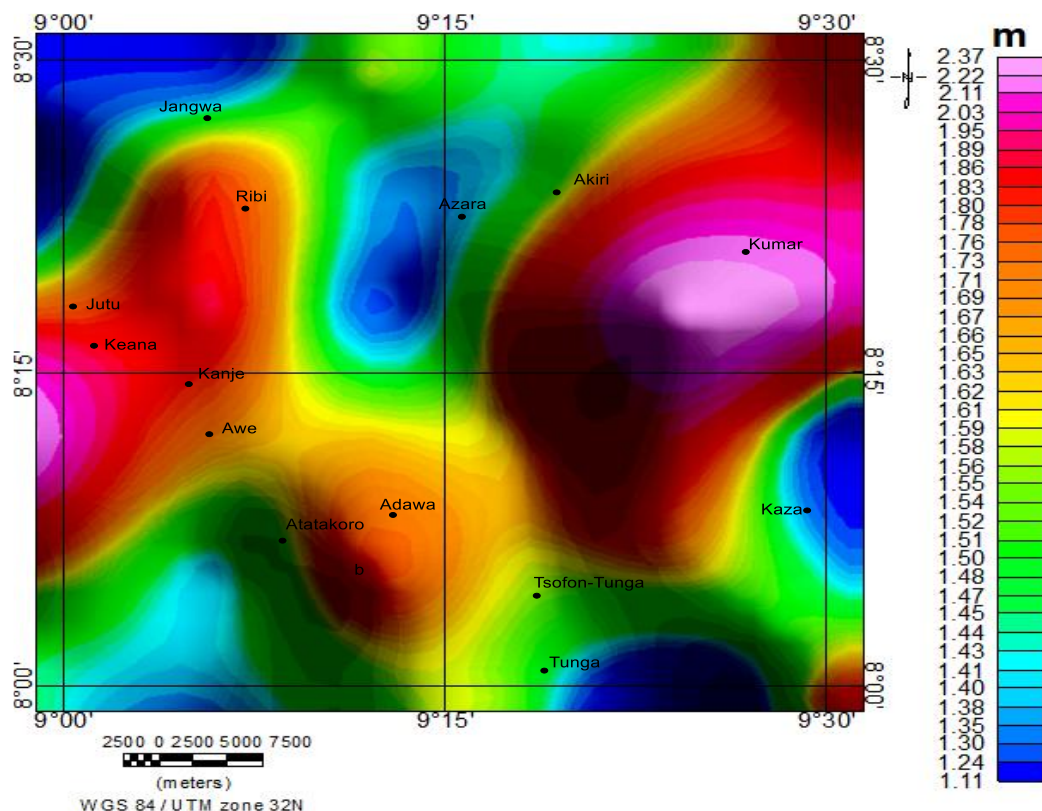


Figure 16: Depth to Top Map of Akiri and Environs

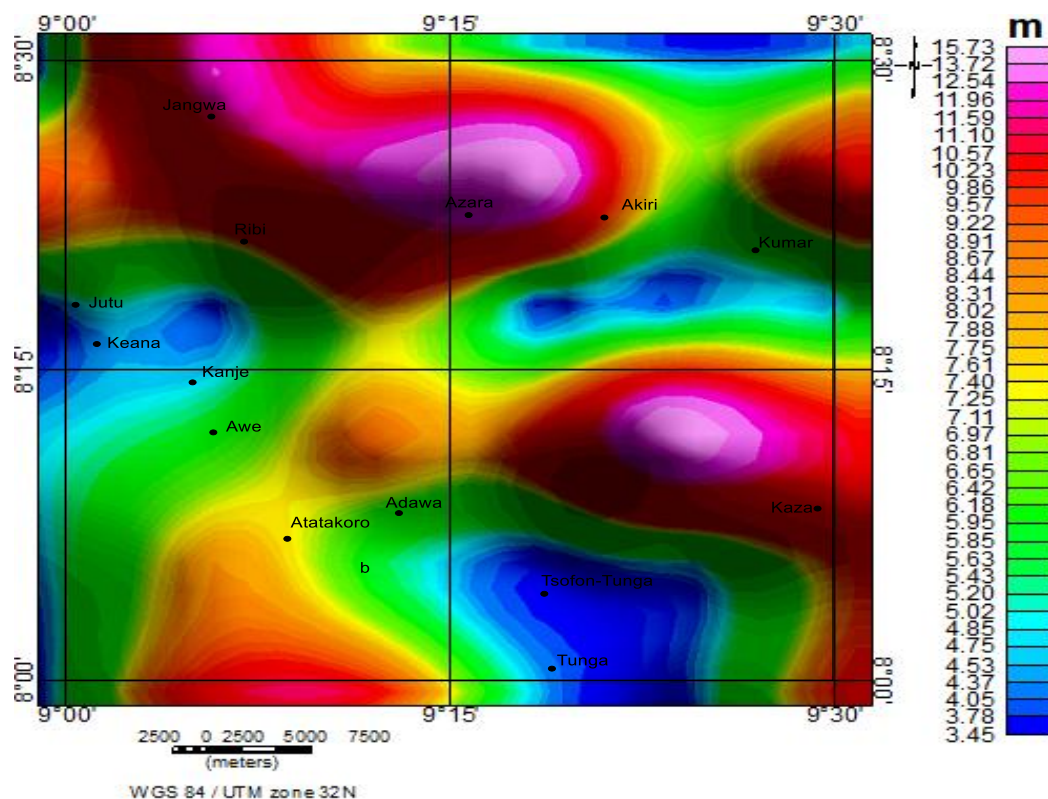


Figure 17: Curie Point Depth Map of Akiri and Environs

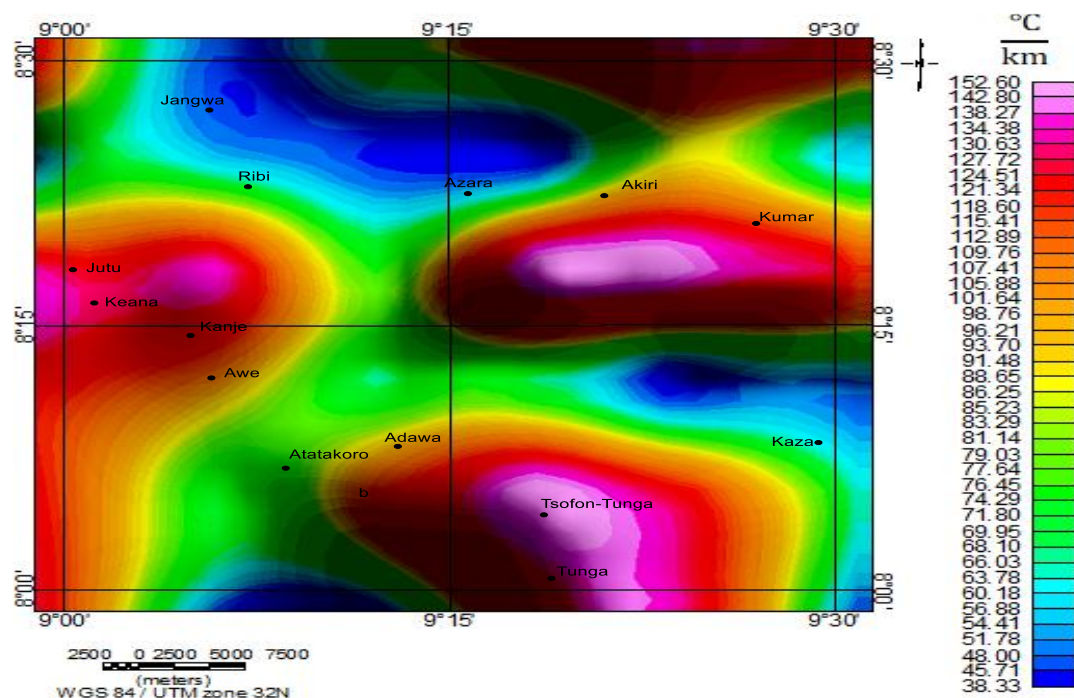


Figure 18: Geothermal Gradient Map of Akiri and Environs

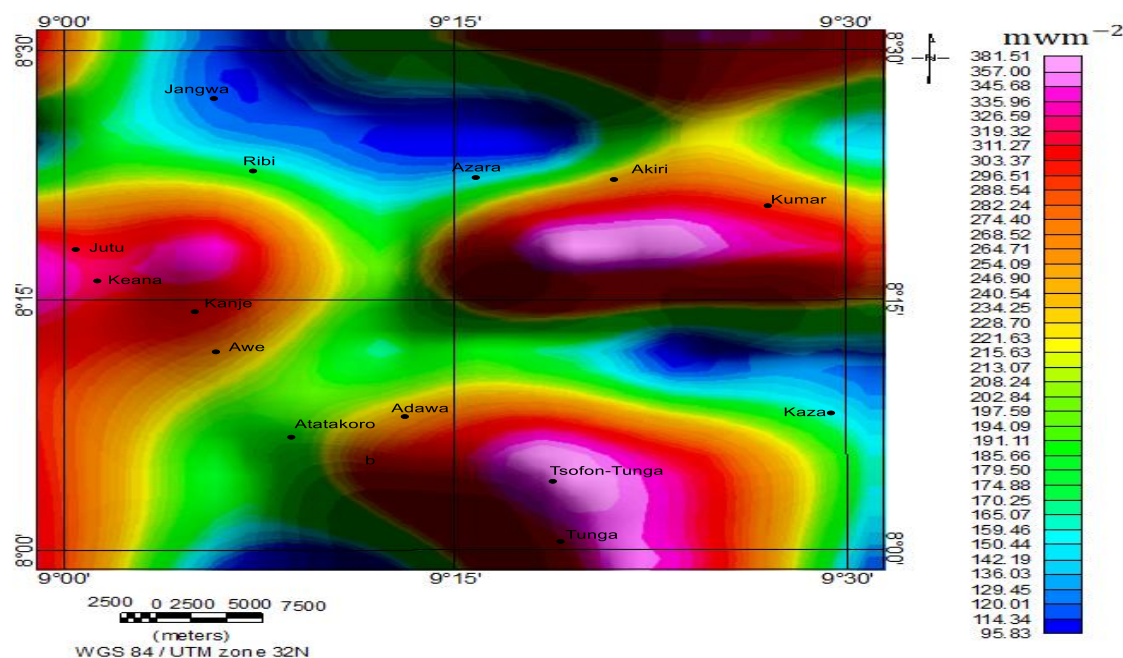


Figure 19: Heat Flow Map of Akiri and Environs

DISCUSSION

Based on the results, both the signals from the total magnetic intensity anomaly map, regional field anomaly map, residual anomaly map and reduced-to-equator anomaly map show significant variations in the magnetic susceptibility of the rocks in the area. Increased intensities are mainly seen in the southeastern and northern regions of the area. These anomalies are probably

associated with rocks rich in magnetite, magmatic intrusions, or volcanic bodies that produce magnetic high responses (Telford et al., 1990). In contrast, regions exhibiting lower magnetic values, particularly in the northeastern and southern sections, are characterized by sedimentary formations or materials with weak magnetic properties (Reeves, 2005). These anomalies suggest differences in the near-surface lithology and structural

characteristics. The areas with low residual values are understood to indicate areas where the basement is situated at a greater depth or where the rock formations exhibit lower magnetic properties (Nabighian et al., 2005; Blakely, 1995). Reduce to the equator (RTE) filters preserve the low inclination angle at the equator that makes the magnetization source horizontal (Figure 6).

The residual anomaly map reveals structural trends that are of shallow origin and that conform to the regional tectonic trends. The minor N-S and dominant NE-SW, NW-SE, NNE-SSW trends are structural orientations that are dominant and are attributed to processes of rifting and deformation of the Earth's crust in the region (Benkheil, 1989). Structural characteristics, including faults, springs, geysers and fractures, are important because they can serve as pathways for the circulation of geothermal fluids (Nabighian et al., 2005; Anudu et al., 2014; Hochstein, 1990).

Reduce to the equator (RTE) filters preserve the low inclination angle at the equator that makes the magnetization source horizontal (Figure 6). The RTE map enhances the design of basement architecture, incorporating the structural features along with their respective orientations. Aids in eliminating the influence of magnetic inclination in regions of low magnetic latitude by aligning the peaks of magnetic anomalies directly above their sources. Based on the fluctuations in magnetic intensity within the study area, two notable magnetic zones were identified. Significant magnetic anomaly values of high amplitude are observed in the western, central, southern, and eastern areas. Nevertheless, comparatively low values of magnetic intensity amplitude are seen in the northern, western, and southern parts of the region (Figure 6). As stated by Ngako et al. (2008), the RTE map predominantly displays northeast-oriented minima and maxima anomalies that generally align with the strike-slip tectonic activities linked to Proterozoic collisional events.

Characterization of Lineaments and Lithological Mapping

Images derived from the derivative filters reveal most structural features, such as inferred faulting, joints, contacts, and, to some extent, the form of certain lithologies (Okpoli & Akinbulejo, 2021). The surface and subsurface horizontal contacts of the intrusion are picked by gradient filters (Blakely, 1995). Structural weaknesses were identified, such as faults, joints, arched sections, and geological contacts. It is commonly used to immediately determine the location of metalliferous ore deposits and fluid migration (Feumoe et al., 2012). Minerals that are highly magnetic mainly concentrate along those structures. The distribution pattern of intrusion largely conforms with geology, and the lineament density shows a few small deviations. The lineaments from the aeromagnetic data are dominant in the southern, eastern, northern and central parts of the area. They are dominant in areas with hot springs. While lineaments extracted from Landsat are randomly dispersed in the area, they are dominant in the southern, northern, eastern and central parts of the area. The superficial lineaments from Landsat coincide with those from aeromagnetic data. It was also observed that lineaments detected from first, second, and total gradient filters had orientations of NE-SW, NW-SE and NNE-SSW directions with a minor N-S trend. Also, structural trends from lineaments extracted from aeromagnetic and Landsat imagery data in the area are mainly NE-SW, NW-SE, and NNE-SSW (Figures 10 and 11). Structural complex density analysis shows that the lineaments are dominant in the western, southern, and extreme

north-central parts of the area. The identified lineaments are used as control areas with high geothermal energy. The lineament density map coincides with areas with high geothermal potential (Figure 12). Because the area is structurally controlled, high structural density areas highlight the value of lineament density maps in the identification of prospective zones (Abdelnasser & Kumral, 2017).

Geothermal Gradient, Depth to Centroid, Depth to Top, Curie Point Depth and Heat Flow over the Study Area and Environs

The upward continuation map at 15 km shows figures that range from about -393 nT to -228 nT. These figures on the upward continuation anomaly map are lower than the total magnetic anomaly map values. The upward continuation map shows a similar pattern of strong and weak magnetic anomalies. A significant negative (long-wavelength) anomaly is observed on the upward continuation map, which is predominantly smoothed and spread throughout the northeastern, central, and southern regions of the area. The northern section of the map consistently displays significant anomalies characterized by long-wavelength, low-amplitude magnetic highs and somewhat larger magnetic lows, indicating that these anomalies are likely linked to deeper geological structures.

The radial power spectrum method was employed to estimate the Curie point depth (CPD), geothermal gradient, and heat flow for each segment. For depth to centroid, deeper depths are in the northwestern, southwestern, eastern, and central parts of the area. Shallow depths are in the southern and eastern parts of the area (Figure 15). Depth to top: deeper depths are in the western, central, and eastern parts of the area, while shallower depths are in the southern, northern, and eastern parts (Figure 16). Curie point depths are well spread in the area. Deeper depths are in the southwestern, central, and eastern parts of the area, while shallower depths are in the western, southern, and eastern parts of the area (Figure 17). Deeper geothermal gradients (Figure 18) are found in the western, southern and northwestern parts of the area, while shallower geothermal gradients are in the northern, southern and extreme southwestern parts of the area. Higher heat flow in the area is found in the western, southern, and northeastern parts of the area (Figure 19), while lower heat flow is in the eastern, western, northern and northwestern parts of the area (Figure 19). The high heat flow values coincide with areas with high lineament densities. Areas with low lineament densities correspond to low heat flow areas (Figure 12). Therefore, it is established that geology and lineaments control geothermal energy in the area. According to Rankenburg et al. (2004), the shallow depths discovered in this study are most likely the consequence of rifting connected to the Benue Trough and magmatic intrusions. They may also be a region of thinner crust with higher heat flow values since they are the sites of several thrust faults linked to the collision tectonics of the Pan-African belt. According to Andrianivo & Ramasirinoro (2010), extensional domains—where significant structures like fractures operate as the geological controls on fluid flow—often contain areas with shallow Curie points. Heat conduction is more likely to occur outside of permeable fracture channel systems, but free convection predominates as the heat transfer mechanism along the permeable fracture path.

Eastern Africa has the potential to produce more than 20 GW of geothermal energy, according to estimates from the Infrastructure

Consortium for Africa and the United Nations Environment Programme (Teklemariam, 2018). This has prompted countries like Comoros, Eritrea, Djibouti, Rwanda, Uganda, and Tanzania to begin investigating geothermal resources. In Zambia, Burundi, and Uganda, new small-scale geothermal power plants are being constructed (Hafner et al., 2018). Heat flows, geothermal activity, and temperature gradients for several African countries are compiled in Table 2. The values obtained fall within the range documented for geothermal provinces and sedimentary basins globally (Nwankwo & Ekine, 2009; Tanaka et al., 1999). Low CPD

values suggest increased subsurface temperatures and potential magmatic activity, indicating a higher geothermal potential (Okubo et al., 1985; Yohanna et al., 2023; Lucky et al., 2026). When the values obtained are compared to those from certain African nations that are leveraging their geothermal energy resources, Nigeria emerges as a country with significant potential for harnessing geothermal energy (Table 2). The value realized is notably higher than that which is obtained from other African nations and the global community.

Table 2: Temperature gradients, Geothermal activity, and Heat flows in various African nations (Modified from Elbarbary et al., 2022)

Country	Geothermal activities	Geothermal gradient (°C/km)	Heat flow (mW)	References
Algeria	DU		100 -120	(Meliani et al., 2016)
Botswana	DU, F		60 – 90	Leseane et al., 2015)
Burundi	DU, ES, EAR	> 60	72	(Sininkayo et al., 2015)
Cameroon		Avg of 72.24	Avg of 180.59	Mono et al., 2018)
Congo		40	30-40	(Schito et al., 2016)
Djibouti	IU, DU, EAR, ES		~ 235	(Saleh et al., 2013)
Egypt	DU	16.3 – 67.4	47.1–195.5	(Abdel Zaher et al., 2018; Elbarbary et al., 2018)
Ethiopia	IU, DU, EAR, ES, PP	60		(Bekele, 2012)
Gabon		Avg 33		(Hodgson et al., 2017)
Ghana			42 ± 8	(Sass & Behrendt, 1980)
Kenya	IU, DU, EAR, ES, PP	69.92 – 111.53	40 – 42	(Githiri et al., 2012; Wheildon et al., 1994)
Nigeria		46.22 - 121.62	105.68 - 227.63	Yohanna et al., 2023
Nigeria		22.701 - 38.770	56.751 - 96.925	Lucky et al., 2026
Nigeria		35.41 - 149.87	88.32 - 382.59	Present study

Conclusion

This study examined the tectonic history and geothermal potential of some areas within the Middle Benue Trough in North-central Nigeria, utilizing data from aeromagnetic studies. Tectonically, the main structural orientations are in the NE-SW, NNE-SSW, and NW-SE, with fewer N-S trends. The lineament density map shows that lineaments influence the potential for geothermal energy and heat flow. Spectral analysis shows that depth to centroid in the area ranges from 2.73 km to 9.09 km, depth to top ranges from 1.11 km to 1.89 km, Curie point depths range from 3.79 to 16.38 km, geothermal gradients range from 35.41 to 149.89 °C/km, and heat flow values range from 88.52 to 382.59 mW/m². These values fall within the range documented for sedimentary basins and geothermal provinces in the world. Shallow Curie point depths suggest heightened subsurface thermal conditions and possible influence from magma, indicating potential for geothermal energy. When compared to a common CPD of 3 °C/100 m or 30 °C/km, and typical thermal conductivity values varying from 105.68 to 227.63 mW/m², the area is deemed to have good geothermal energy potential. Thus, the area has very significant potential for geothermal energy resources. The most important and practical conclusion of the study is that the area has high potential for geothermal energy resources that need to be investigated using boreholes, gravity and geochemical data. Nigerian Government needs to make the search for energy its priority to tackle the energy crisis in the country.

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