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Geophysical investigation of geothermal energy resource potential for electricity generation: A case study of Ikogosi –Ado Ekiti and Ijebu Ife, South Western Nigeria

JULIET E. EMUDIANUGHE and MAUREEN OLUOHA EKECHIKWE *

Department of Earth Sciences, Federal University of Petroleum Resources, Effurun 330102, Delta State, Nigeria.

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Abstract

This research endeavors to access the spectral depth, basement structure variability, and deduce heat and geothermal distribution of the study areas Ijebu-Ife and Ikogosi. Aeromagnetic and geological methods were applied in the analysis using Oasis Montaj Surfer 8 and Mat Lab using sheets 244 and 281. Geological analysis revealed that Ikogosi was found to be underlain by three rock units; quartz schist, quartz mica schist, and quartzite, while Ijebu-Ife is underlain by Quartzite, quartzite Schist, and migmatite. The Ijebu-Ife Curie point depth values ranges from (13.10- 22.30) km, the geothermal gradient values ranges from (25.01– 37.123) °C/km and the heat flow values ranges from (68.736- 108.079) mW/m2. The SE edge,Abigi, Agbure, and Ilushin hosts the highest values of heat flow and geothermal gradient with corresponding shallowest values of curie point depth (Fig. 4.2 a-c). Regions like Omo, Oso, Kojala, Oniparaja also good geothermal manifestations. Generally, for a viable geothermal reservoir, a heat flow range of (80 - 100) mW/m2is recommended, hence it can be inferred that every region on the study area could be considered as having good prospect except within the Northern region, Gbamu of the study area with low heat flow below 80 mWm-2. The Ikogosi Curie point depth values ranges from (6.89- 16.15) km, the geothermal gradient values ranges from (39.2– 84.74) °C/km and the heat flow values ranges from (96.05- 207.31) mW/m2 (Figs. 4-1 a-c). The NW edge covering Ofale, Iye, Ifere, Iddo-Ekiti, Ijero-Ekiti, Aramoko, and Ikogosi hosts the highest anomalous values of heat flow and geothermal gradient with corresponding shallowest values of Curie point depth (Fig. 4.2 a-c). Generally, for a viable geothermal reservoir, a heat flow range of 80 to 100 mW/m2is recommended, hence it can be inferred that every region on the study area could be considered as having good prospect of the study area with high heat flow above 80 – 100 mWm-2.

Keywords: Geothermal Energy; Curie Point Depth; Geothermal Gradient; Heat Flow; Aeromagnetic Survey; Spectral Analysis

1. Introduction

The global pursuit of a cleaner, safer environment and the vision of a connected global village have driven nations to seek sustainable energy alternatives. In Nigeria, industries have traditionally relied on self-generated power through fuel and diesel generators to meet their energy needs. However, these methods have proven inefficient, costly, and incapable of supporting a consistent, widespread power supply. Furthermore, the reliance on fossil fuels, such as coal, oil, and natural gas, contributes to the emission of greenhouse gases, including carbon dioxide (CO_2), which exacerbates climate change, depletes the ozone layer, and leads to severe environmental challenges such as droughts, desertification, and coastal erosion (IEA, 2021; Ashish Kumar K., Md Mijanur Rahman, 2020).

Given these inefficiencies and environmental impacts, the need for cleaner, more reliable energy sources has become increasingly urgent. Geothermal energy, a renewable and sustainable energy source, offers a promising solution. Geothermal energy is one of the safest and cleanest forms of energy, as it harnesses the heat from the Earth's interior. Unlike fossil fuels, it does not emit harmful greenhouse gases and is not subject to depletion, making it a constant and

* Corresponding author: MO EKECHIKWE

reliable power source. However, identifying geothermal reservoirs remains a significant challenge. To overcome this, integrating geophysical methods with geological data is essential for locating and utilizing geothermal energy as a sustainable power generation source.

Countries like the USA, China, Italy, and Israel have already leveraged geothermal energy for power generation, exploiting geothermal reservoirs from discovered fields. Their success highlights the potential for clean, renewable energy that significantly reduces environmental impact. Nigeria, too, can benefit from this energy transition. Harnessing geothermal energy could provide a steady and efficient power supply, helping to mitigate the problem of irregular electricity in parts of the country. By shifting to geothermal energy, Nigeria can reduce its reliance on non-renewable energy sources and meet its growing energy needs more cleanly and sustainably.

1.1. Non-Renewable Energy

Non-renewable energy sources, such as fossil fuels (coal, oil, and natural gas) and nuclear energy derived from uranium, are finite and cannot be replenished within a human lifetime. Fossil fuels originate from the remnants of prehistoric flora and fauna that underwent geological transformations over millions of years. While these fuels have been the primary drivers of industrialization and economic growth, their extraction and combustion release large amounts of CO2 and other greenhouse gases, contributing to climate change and air pollution.

Nuclear energy, although free from direct greenhouse gas emissions, poses significant risks, including the potential for nuclear accidents, radioactive waste disposal challenges, and concerns over nuclear weapons proliferation. As the environmental and social costs of non-renewable energy sources become more apparent, there is a growing global shift toward renewable and sustainable energy solutions. This shift is supported by efforts to increase energy efficiency, promote renewable energy technologies, and implement policies aimed at mitigating climate change.

1.2. Renewable Energy

Renewable energy (RE) is defined as energy derived from natural processes—such as solar, wind, geothermal, biomass, hydropower, and ocean energy—that are continuously replenished by nature. These energy sources are sustainable, environmentally friendly, and contribute little to climate change (Vijay et al., 2015; Manzella, 2017). Geothermal energy, in particular, stands out as one of the most reliable and efficient forms of renewable energy. Unlike solar and wind energy, which depend on weather conditions, geothermal energy is consistent, as it draws heat from the Earth's interior.

This proposal focuses on the geophysical investigation of geothermal energy potential in Ikogosi-Ado Ekiti and Ijebu Ife, Southwestern Nigeria. The study aims to integrate geological and geophysical methods to identify and characterize potential geothermal fields and reservoirs. By doing so, it seeks to lay the groundwork for the development of geothermal energy as a reliable and sustainable source of electricity in Nigeria.

1.3. Study Area

Ikogosi, situated in Ado Ekiti within the Southwestern Nigerian Basement Complex, is characterized by diverse geological formations. The area is bounded to the southeast and south by migmatite, while the extreme northern region is dominated by porphyritic schist. To the northeast, the geology consists of a mixture of schist and phyllites. The area is primarily underlain by three distinct rock units: quartz schist, quartz mica schist, and quartzite. At the base of Ikogosi, where the cold and hot springs meet, quartz mica schist is the dominant rock, with fine grains of mica and quartz. As one moves upward along the outcrop of the warm spring, the quartz grains become progressively coarser until they transition into quartz minerals.

Ijebu Ife, located in Erin, Ogun State, also falls within the Southwestern Nigerian Precambrian Basement Complex. The area is underlain by quartzite, quartzite schist, and migmatite. A schist belt forms a ridge that extends from Ekiti through Osun and into Ogun State. Ijebu Ife is predominantly underlain by quartzite schist, with occasional quartzite layers in certain areas. The region is bounded to the north, west, and central areas by schist and quartz, while the northeastern region is characterized by migmatite. The northernmost and eastern parts of the area are similarly dominated by migmatite. These geological features highlight the significant potential for geothermal energy exploration in both Ikogosi and Ijebu Ife (Ashish Kumar K., Md Mijanur Rahman, 2020).

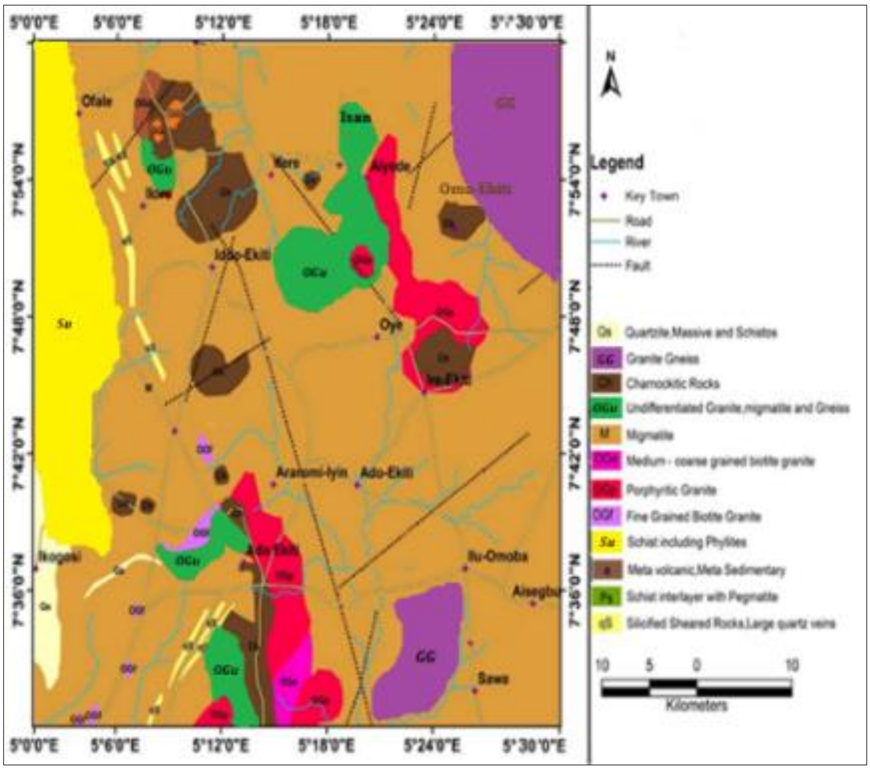

Figure 1 Map of ikogosi and its environs and the minerals found there

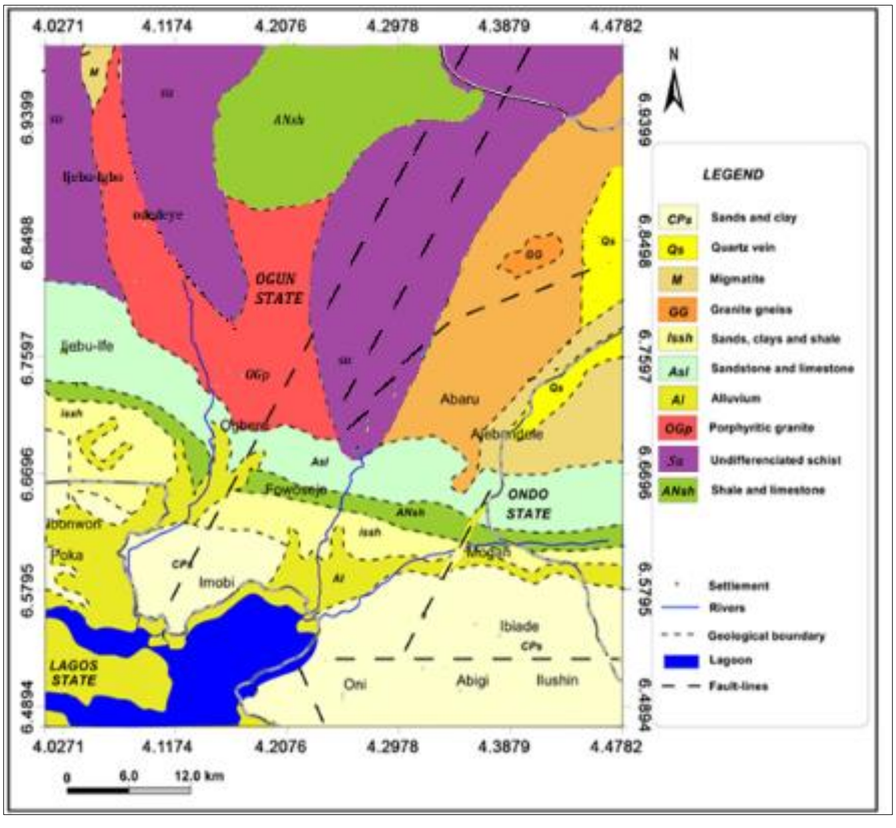

Figure 2 Map of ijebu igbo and its environs indicating various minerals in different location

2. Materials and Methods

The survey was conducted using Cessna Caravan and Cessna 406 aircraft, equipped with Scintrex CS3 Cesium Vapour magnetometers, which are renowned for their sensitivity and ability to detect subtle magnetic variations.

The study outlines the comprehensive methodology employed to assess the geothermal energy resource potential in the Ikogosi-Ado Ekiti and Ijebu-Ife regions of Southwestern Nigeria. The approach integrates both geophysical and geological methods, emphasizing aeromagnetic data acquisition, processing, analysis, and interpretation. Key geothermal parameters, such as Curie point depth, geothermal gradients, and heat flow, were estimated to identify areas with high geothermal energy potential for future exploration and development.

2.1. Research Design

The research was conducted in multiple phases, combining aeromagnetic surveys, advanced geophysical data processing, spectral analysis, and the incorporation of geological data. The workflow of the study was structured as follows:

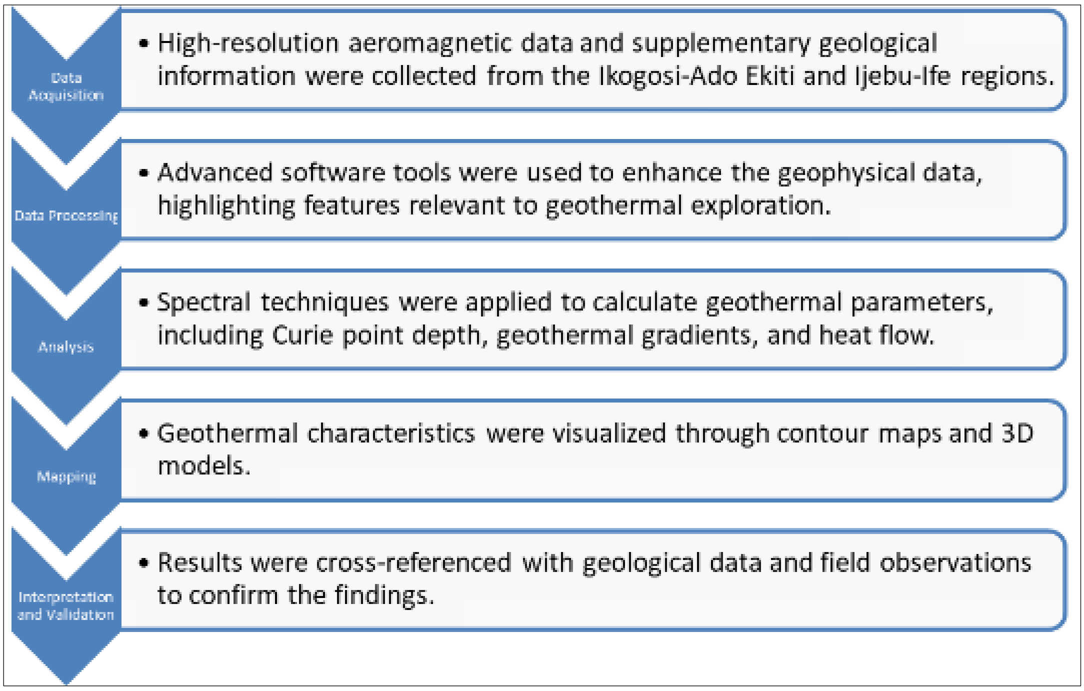

Figure 3 Diagram of research design

2.2. Data Acquisition

The first step of the study involved acquiring high-resolution geophysical data to evaluate the subsurface geothermal characteristics. Aeromagnetic survey data was the primary source of information, providing detailed insights into variations in the Earth's magnetic field, which are indicative of geothermal anomalies.

2.2.1. Aeromagnetic Survey

The aeromagnetic survey was conducted by Fugro Airborne Surveys and covered the Ikogosi-Ado Ekiti and Ijebu-Ife regions. Aeromagnetic surveys detect magnetic field variations due to differences in rock types and geological structures, helping to identify potential geothermal reservoirs. Key specifications of the survey were:

- Magnetic Data Recording Interval: Data was recorded every 0.1 seconds, corresponding to a ground resolution of approximately 7 meters, ensuring high spatial precision.
- Sensor Terrain Clearance: The magnetometer sensors were flown at an average altitude of 80 meters above the terrain, providing detailed detection of subsurface magnetic anomalies.
- Flight Line Spacing: Flight lines were spaced 500 meters apart to ensure thorough coverage of the study area.
- Tie Line Spacing: Tie lines, spaced 5000 meters apart, were used to correct for lateral drift in the data.

- Flight Line Orientation: The main flight lines were oriented at 135 degrees, while tie lines were oriented at 45 degrees.
- Navigation System: The Novatel 3151R/Omnistar Real-Time Differential GPS (RTDGPS) system was used to track the flight path with high accuracy.

2.3. Data Processing

Once the aeromagnetic data was acquired, several data processing steps were implemented to transform the raw data into a suitable format for analysis. This stage involved removing noise and enhancing the geophysical features relevant to geothermal exploration.

2.3.1. Oasis Montaj Software

The Oasis Montaj platform, developed by Geosoft, was used to process and visualize the aeromagnetic data. This software offers advanced tools for geophysical data management and interpretation. The main stages in handling data involved:

- IGRF Correction: The International Geomagnetic Reference Field (IGRF) was applied to the data to remove the regional magnetic field and isolate local magnetic anomalies critical for geothermal exploration.
- Gridding: The aeromagnetic data was interpolated onto a 50-meter grid to create a continuous representation of magnetic field variations, facilitating the identification of subsurface structures.
- Filtering: High-pass filters were applied to highlight shallow magnetic anomalies, which may indicate near-surface geothermal systems. Low-pass filters were used to emphasize deeper geological structures, such as faults or fractures that can influence geothermal fluid circulation.
- Gradient Maps: Horizontal and vertical gradient maps were generated to emphasize geological boundaries and fault zones, which are essential in understanding geothermal systems. These maps highlight areas where rapid changes in the magnetic field occur, often associated with fault lines or intrusive bodies that could serve as geothermal heat sources.

3.3.2 Fast Fourier Transform (FFT)

The Fast Fourier Transform (FFT) technique was applied to the processed aeromagnetic data to decompose the magnetic signal into its frequency components. This technique is essential for assessing the depth of magnetic sources and identifying the depth of the Curie point. Key steps included:

- Sub-block Analysis: The study area was divided into smaller, overlapping sub-blocks to ensure localized spectral analysis, providing a more detailed understanding of geothermal features in different parts of the region.
- Spectral Energy Plotting: The FFT decomposes the magnetic data into frequency components, and the logarithm of the spectral energy was plotted against the wave number (spatial frequency). The slope of this plot was used to estimate the depth of magnetic sources, including the Curie point.
- Curie Point Depth Calculation: The depth to the Curie point, where magnetic minerals lose their magnetism due to high temperatures, was calculated from the spectral energy plots. Shallower Curie point depths indicate higher geothermal potential, as heat-producing rock formations are closer to the surface.

2.3.2. MATLAB for Spectral Analysis

MATLAB software was used for detailed spectral analysis and the computation of geothermal parameters based on the processed aeromagnetic data. Key processes performed with MATLAB included:

- Geothermal Gradient Estimation: The geothermal gradient, which measures the rate of temperature increase with depth, was calculated from the Curie point depths. This parameter helps identify areas with high geothermal energy potential.
- Heat Flow Calculation: Heat flow values were derived from the geothermal gradient and the thermal conductivity of the subsurface rocks. Elevated heat flow measurements indicate considerable geothermal potential.

2.3.3. Surfer 8 Software

The Surfer 8 software was used to create contour maps and 3D models that visually represent the geothermal characteristics of the study area. These visualizations were crucial for identifying geothermal hotspots and guiding future exploration efforts. Keymaps generated included:

- Geothermal Gradient Maps: These maps display the variation in the geothermal gradient across the study area, highlighting regions with steep temperature increases that may host geothermal reservoirs.
- Heat Flow Maps: These maps indicate areas with high thermal energy output, which are primary targets for geothermal exploration.
- Magnetic Intensity Maps: These maps show the distribution of magnetic anomalies linked to heat-producing subsurface geological formations.

2.4. Spectral Analysis and Depth Estimation

Spectral analysis of the aeromagnetic data was a critical step in estimating subsurface thermal characteristics. The Fast Fourier Transform (FFT) played a central role in this analysis, enabling the estimation of Curie point depth, geothermal gradients, and heat flow.

2.4.1. Spectral Decomposition

The aeromagnetic data was broken down into its frequency components using the FFT, which were then examined to evaluate the depth of the magnetic sources. The energy spectrum of each sub-block was plotted, and the depth to the bottom and top of magnetic sources was calculated from the slope of the energy spectrum.

2.4.2. Curie Point Depth Estimation

The Curie point depth was estimated by analyzing the spectral energy plots. The Curie point represents the depth at which magnetic minerals lose their magnetism due to high temperatures, and it is a key indicator of geothermal heat sources. Shallower Curie point depths indicate higher geothermal energy potential, as heat-producing rock formations are closer to the surface.

2.4.3. Geothermal Gradient and Heat Flow Estimation

Based on the Curie point depth estimates, the geothermal gradient and heat flow were calculated. The geothermal gradient assesses how temperature rises as depth increases, whereas heat flow indicates the quantity of heat emanating from the Earth's interior. Areas with steep geothermal gradients and high heat flow are considered to have significant geothermal energy potential.

2.5. Generation of Geological and Geothermal Maps

Several critical maps were generated to visualize the geothermal potential of the study area. These maps are essential tools for identifying regions with high geothermal energy potential and guiding future exploration efforts. Keymaps included:

- Curie Point Depth Maps: These maps display variations in Curie point depth across the study area, with shallower Curie depths indicating regions with higher geothermal potential.
- Geothermal Gradient Maps: These maps illustrate how temperature increases with depth, identifying areas with steep gradients that may host geothermal reservoirs.
- Heat Flow Maps: These maps highlight regions where significant amounts of heat are escaping from the Earth's interior, marking prime targets for geothermal exploration.

2.6. Interpretation of Results

The processed data and generated maps were interpreted to assess the geothermal potential of the study area. The interpretation focused on identifying areas with shallow Curie point depths, high geothermal gradients, and elevated heat flow, all of which suggest significant geothermal energy potential. Key considerations during interpretation included:

- Geological Structures: The identified magnetic anomalies were correlated with known geological structures such as faults and fractures, which can enhance geothermal fluid circulation and heat transfer.

- Surface Geothermal Manifestations: The geophysical data was cross-referenced with surface geothermal manifestations, such as hot springs, to validate the findings and ensure the accuracy of the geothermal potential estimates.

2.7. Validation and Cross-Referencing with Geological Data

The results of the geophysical analysis were validated by cross-referencing them with existing geological maps and field data. This validation ensured that the identified geothermal anomalies were consistent with known geological formations and surface geothermal features.

This comprehensive methodology provides a reliable framework for assessing geothermal energy potential in the Ikogosi-Ado Ekiti and Ijebu-Ife regions. By integrating advanced geophysical processing with geological data, the study successfully identified key geothermal parameters such as Curie point depth, geothermal gradients, and heat flow, which are essential for pinpointing geothermal hotspots. This approach offers a robust basis for future geothermal exploration and development in Southwestern Nigeria.

3. Results

3.1. Data interpretation of the IJEBU IFE CPD map

The map in Figure 9, uses a color scheme where blues and purples represent areas with the deepest Curie points (lowest heat flux), while reds and oranges indicate the shallowest Curie points (highest heat flux). Areas with shallower Curie points have greater potential for geothermal energy development due to the higher heat flow. In regions with high geothermal heat flux, several minerals can be associated with geothermal energy potential. Generally, there's an inverse relationship between CPD and geothermal heat flux. Regions with shallower CPDs (e.g., 1000 m) often have higher heat fluxes (e.g., 100 mW/m^2), while deeper CPDs (e.g., 5000 m) correspond to lower heat fluxes (e.g., 50 mW/m^2).

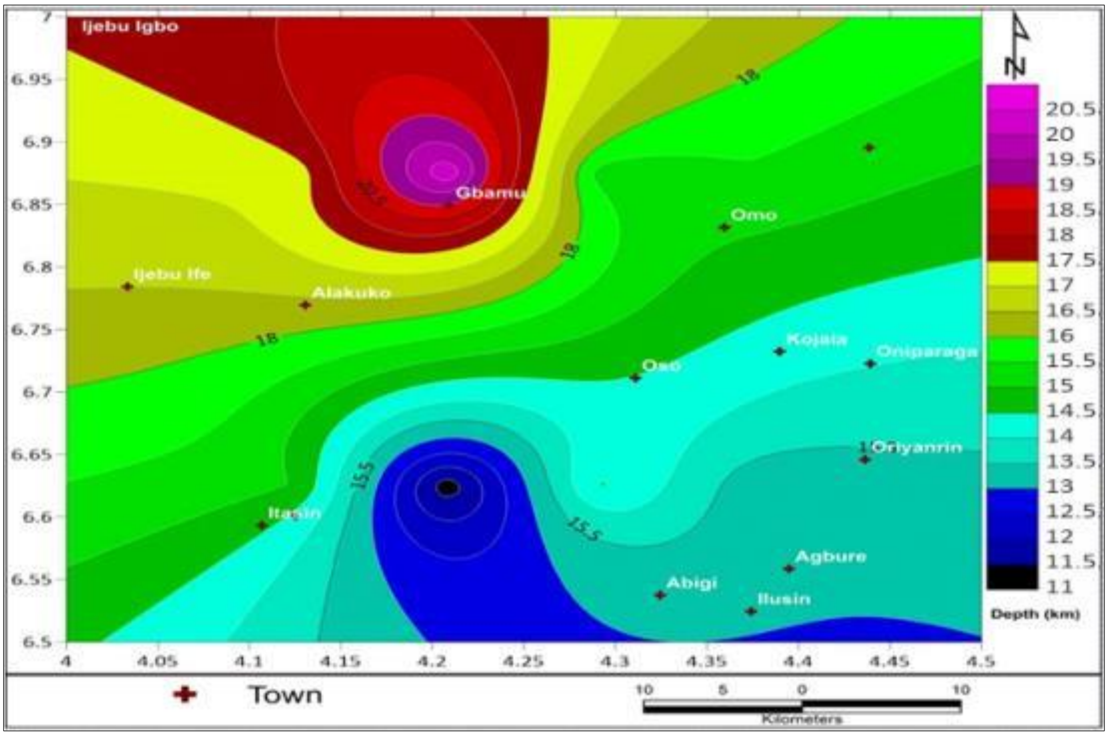

Figure 4 The IJEBU IFE CPD map

Other factors like rock type, tectonic activity, and fluid circulation can influence this relationship. This is typically measured in meters (m). It represents the depth at which the Earth's temperature reaches the Curie point, where ferromagnetic minerals lose their magnetic properties.

3.1.1. IJEBU IFE geothermal gradient map

The recorded temperature per depth is between 24 to 42oC/KM. Warm Colors (Reds, Oranges, and Yellows) Represent higher geothermal gradients, indicating a faster increase in temperature with depth. These areas are typically of greater interest for geothermal exploration due to the potential for higher subsurface temperatures Cool Colors (Blues, Greens) Indicate lower geothermal gradients, suggesting a slower increase in temperature with depth. While not devoid of potential, these areas are generally less promising for geothermal development. The provided geothermal gradient map for Ijebu Igbo reveals significant variations in subsurface temperature increase with depth. The presence of areas with notably high geothermal gradients, particularly around Gbamu and Itasin, suggests promising prospects for geothermal exploration and development.

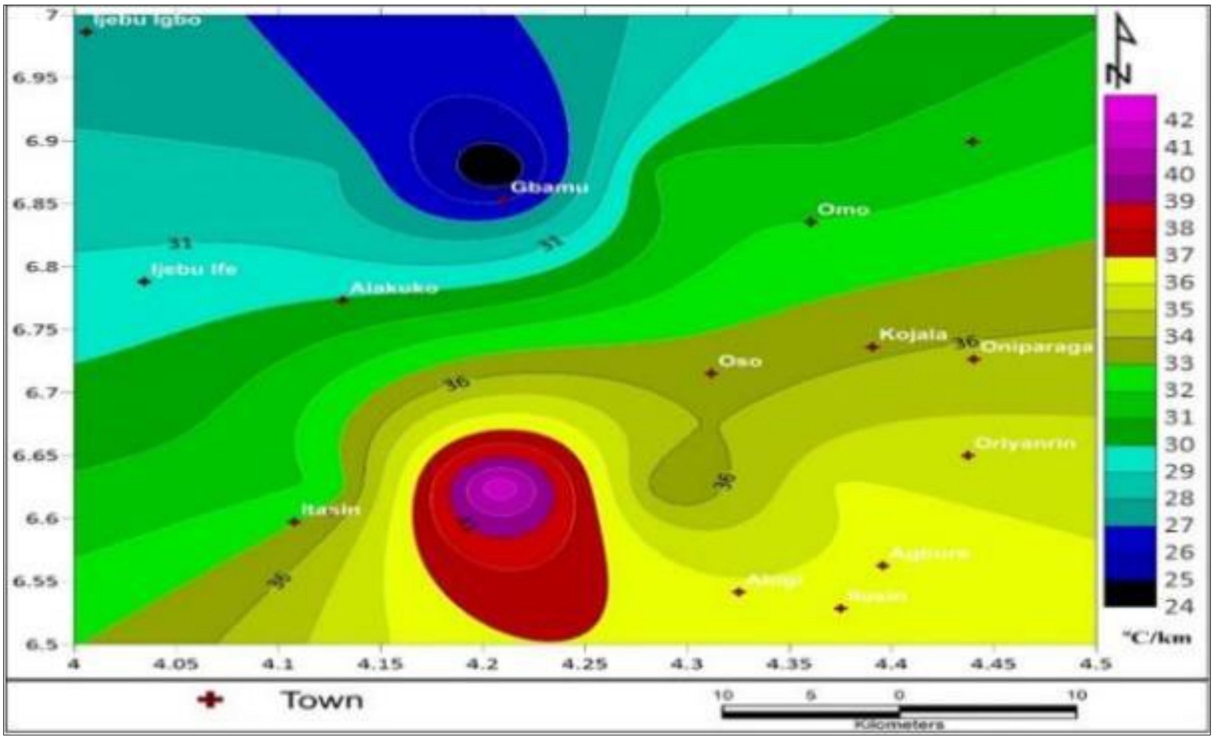

Figure 5 IJEBU IFE geothermal gradient map

3.1.2. Data interpretation for IJEBU IFE heat flow map

The heat flow map measures heat flow which is the amount of heat transferred through a unit area per unit time. The central and southern parts of the map exhibit higher heat flow values, indicating potential geothermal hotspots. The measured values range from 64 to 108 mm-2. Warm colors (reds, oranges, yellows) represent higher heat flow values, indicating areas with greater heat escaping from the earth's interior. These areas are typically of higher interest for geothermal exploration due to the potential for higher subsurface temperatures. Cool colors (blues, greens) indicate lower heat flow values, suggesting less heat escaping from the earth's interior. While not devoid of potential, these areas are generally less promising for geothermal development. The provided heat flow map for ijebu Igbo reveals significant variations in heat flow across the region. The presence of areas with notably high heat flow values, particularly around Gbamu and itasin, suggests promising prospects for geothermal exploration and development.

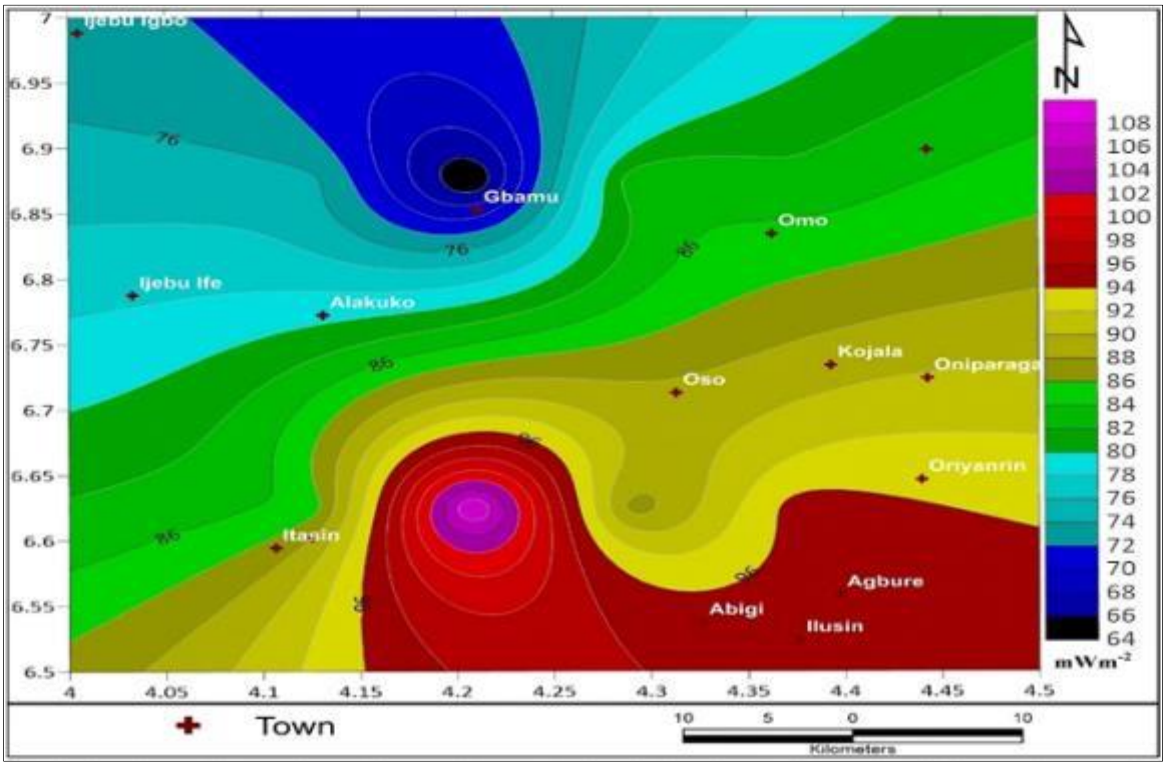

Figure 6 IJEBU IFE heat flow map

3.1.3. IJEBU IFE total magnetic intensity map

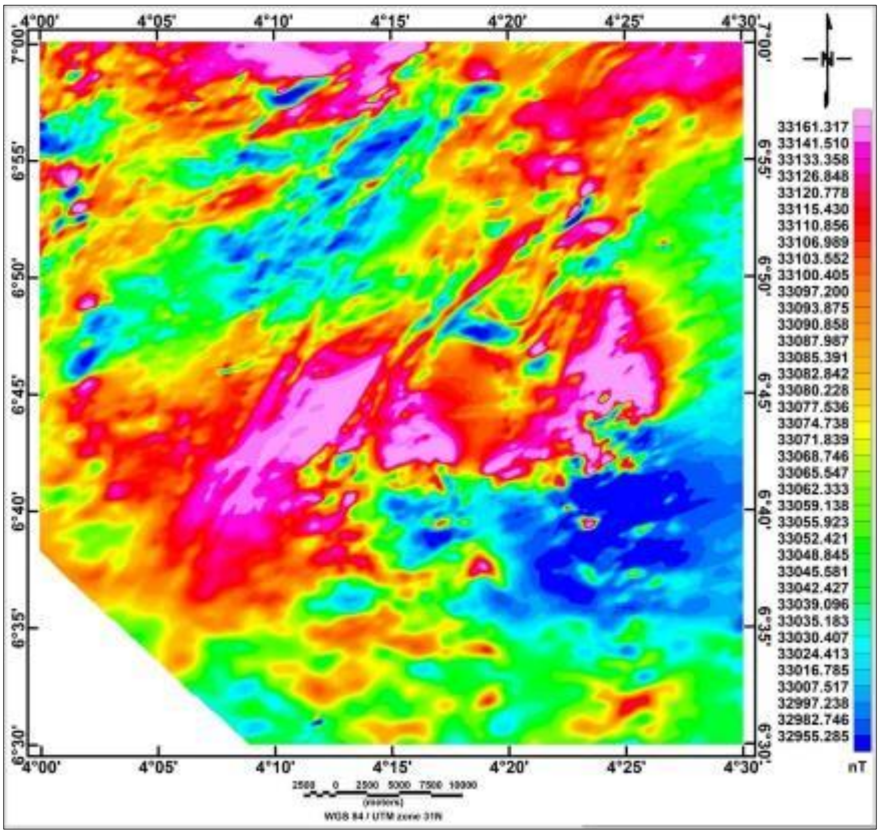

Figure 7 IJEBU IFE total magnetic intensity map

The map provides clues about the distribution of different rock types, with igneous and metamorphic rocks (associated with higher magnetic intensities) potentially linked to heat sources. Areas with lower magnetic intensities may indicate sedimentary basins, which can serve as potential reservoirs for geothermal fluids. The total magnetic intensity values on the map range from approximately 32955 nT to 33161 nT. The unit of measurement is nanoTeslas (nT). Warm Colors (Reds, Oranges, Yellows) Generally represent areas with higher magnetic intensities, which often correlate with igneous and metamorphic rocks. These rock types can be associated with tectonic activities and potential heat sources for geothermal systems. While Cool Colors (Blues, Greens)Indicate lower magnetic intensities, often associated with sedimentary rocks. While not directly indicative of geothermal potential, these areas might contain sedimentary basins that can act as reservoirs for geothermal fluids. The provided total magnetic intensity (TMI) map offers valuable insights into the subsurface geology, which can indirectly inform geothermal exploration.

3.1.4. Data interpretation for IJEBU IFE residual magnetic anomaly map

The residual magnetic anomaly map provides valuable insights into the subsurface geology of the Ijebu Igbo region, which can indirectly inform geothermal exploration. Areas with pronounced magnetic anomalies, especially those characterized by sharp gradients or closures, warrant further investigation. The map reveals several residual magnetic anomalies of varying intensities and extents, suggesting diverse subsurface geology. Areas with high residual magnetic anomaly gradients, particularly those associated with circular or linear features could indicate potential geothermal targets such as intrusive bodies or fault zones, which often act as conduits for geothermal fluids. The residual magnetic anomaly values on the map range from approximately -105.441 nT to 91.392 nT. The unit of measurement is nanoTeslas (nT). Warm Colors (Reds, Oranges, Yellows) Represent positive residual magnetic anomalies, indicating areas with stronger magnetic variations from the regional field. These areas often correspond to subsurface geological structures like igneous intrusions, which can be associated with geothermal activity while Cool Colors (Blues, Greens) Represent negative residual magnetic anomalies, indicating areas with weaker magnetic variations from the regional field. These areas are typically associated with sedimentary rocks, which may have lower geothermal potential.

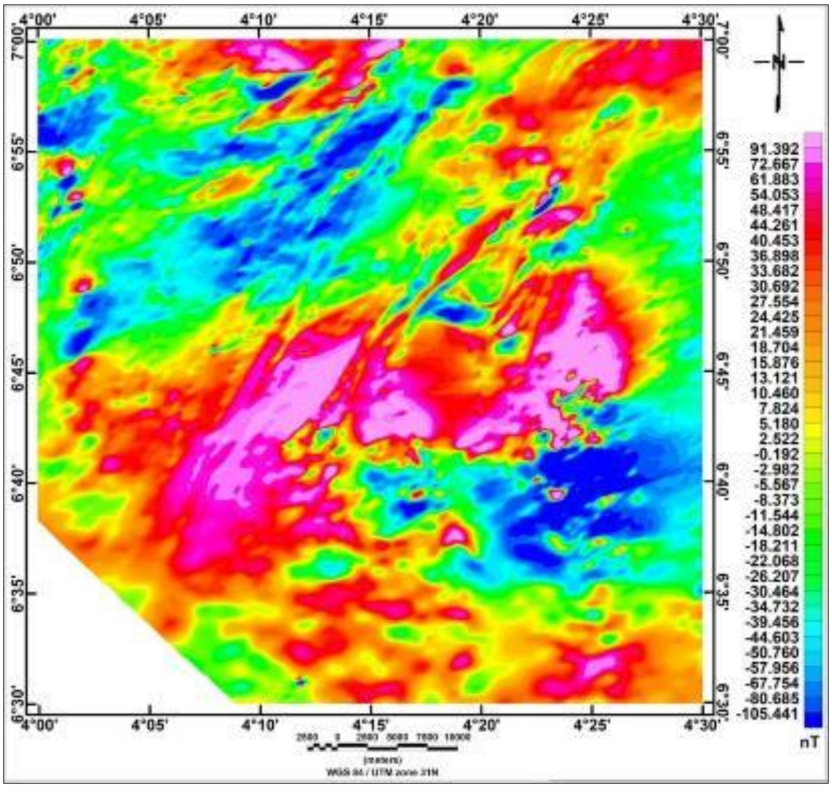

Figure 8 IJEBU IFE residual magnetic anomaly map

3.1.5. Data interpretation for ADO-EKITI curie point depth map

Based on the map, the Curie point depth at Ikogosi appears to be within the range of 12-14 km, falling within the average Curie point depth for geothermal areas. The surrounding areas of Ikogosi with even shallower Curie point depths, indicated by warmer colors, should be considered as potential geothermal prospects. A shallower Curie point depth often correlates with higher heat flow, suggesting increased geothermal potential in these areas. Warm Colors (Reds, Oranges, and Yellows) Represent shallower Curie point depths, indicating closer proximity of the Curie point isotherm (where magnetic minerals lose their magnetization) to the Earth's surface. These areas often correspond to regions with higher heat flow and potential geothermal activity while Cool Colors (Blues, Greens): Represent deeper Curie point depths, indicating a greater distance of the Curie point isotherm from the Earth's surface. These areas generally have lower heat flow and reduced geothermal potential. The Curie point depth map provides valuable insights into the geothermal potential of the Ikogosi region. By identifying areas with shallower Curie point depths, potential geothermal targets can be prioritized for further exploration.

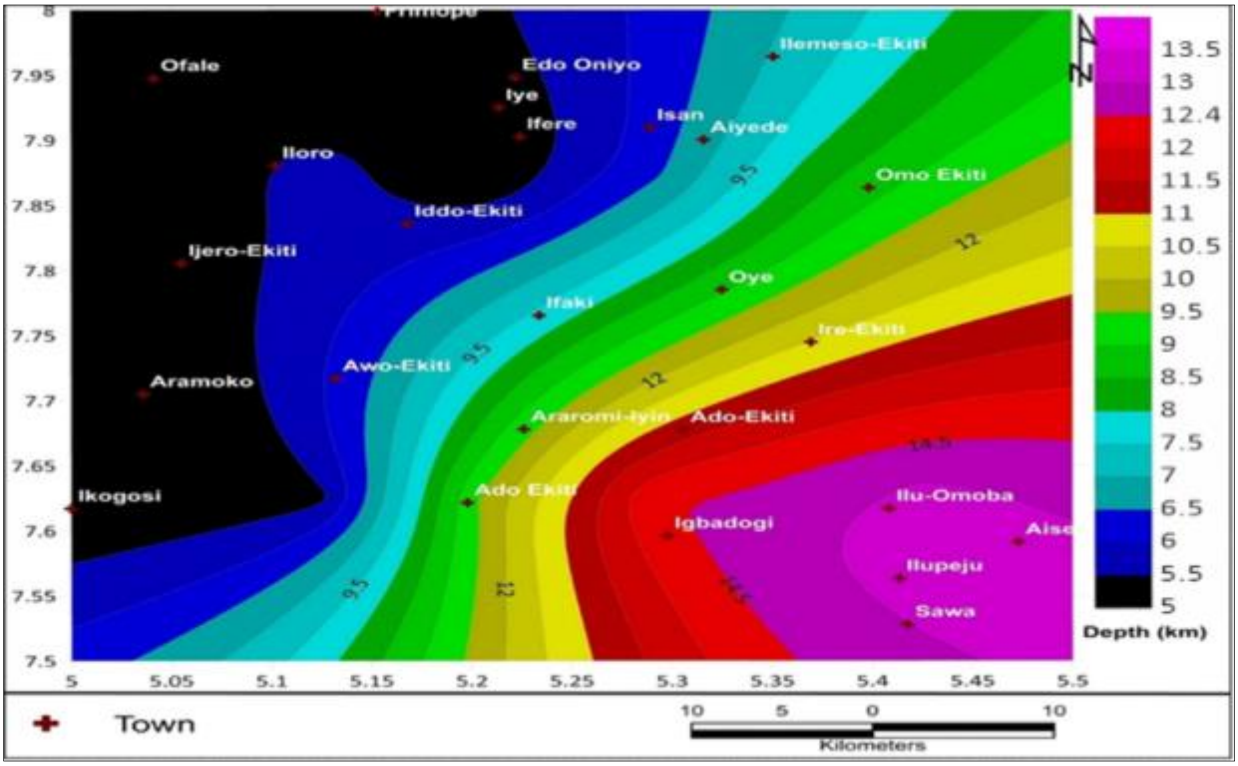

Figure 9 ADO-EKITI CURIE POINT DEPTH MAP

3.1.6. Data interpretation for ado-ekiti geothermal gradient contour map

Specific areas within Ado-Ekiti exhibit higher geothermal gradients, particularly in the southern and eastern parts, indicating potential geothermal hotspots. Geothermal gradients vary within the region, highlighting the importance of targeted exploration efforts. The city itself is situated within an area of moderate geothermal gradient, which could potentially support geothermal direct-use applications. Warm Colors (Reds, Oranges): Represent higher geothermal gradients, indicating a faster increase in temperature with depth. These areas are typically of greater interest for geothermal exploration due to the potential for higher subsurface temperatures. Cool Colors (Blues, Greens) Indicate lower geothermal gradients, suggesting a slower increase in temperature with depth. While not devoid of potential, these areas are generally less promising for geothermal development. The geothermal gradient values on the map are represented by contour lines with values from 5 to 13.5. The unit of measurement for geothermal gradient is °C/km (degrees Celsius per kilometer). The provided geothermal gradient contour map for Ado-Ekiti reveals variations in subsurface temperature increase with depth. The presence of areas with notably high geothermal gradients suggests promising prospects for geothermal exploration and development.

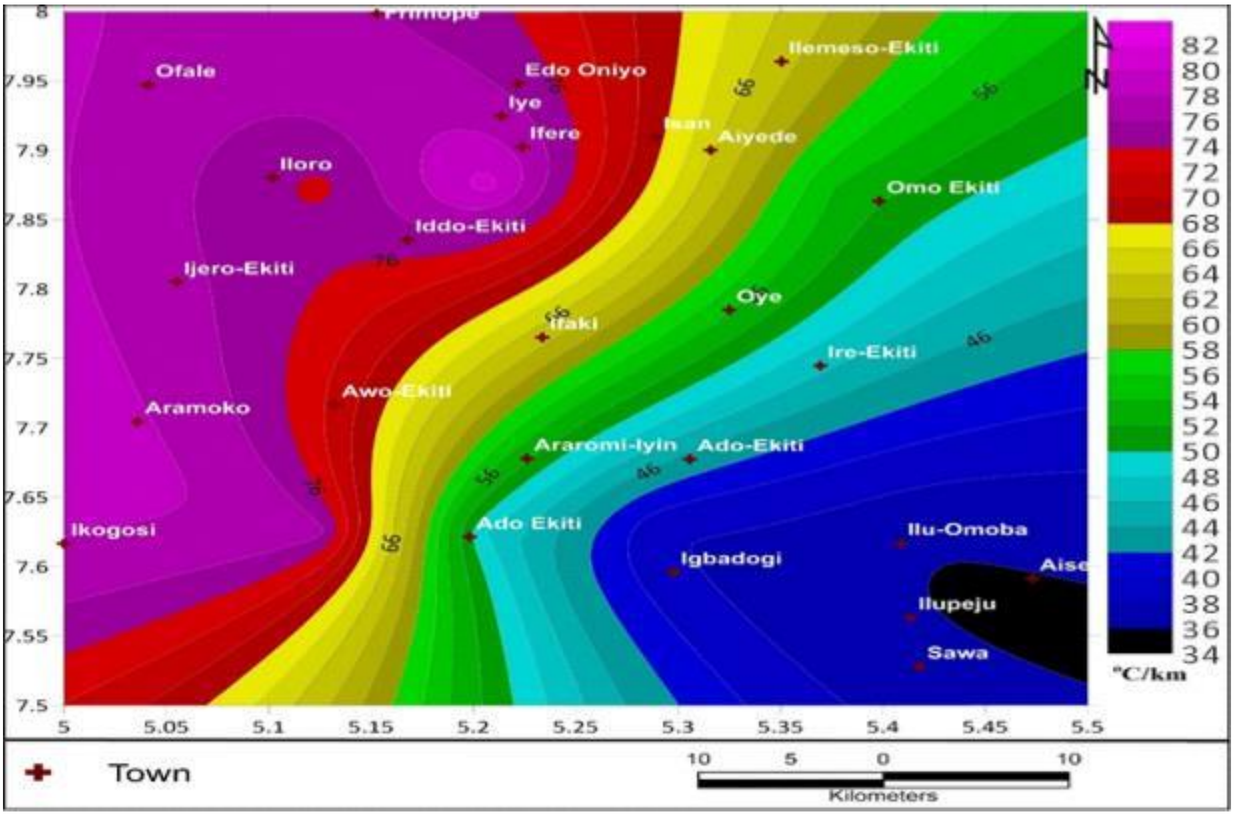

Figure 10 ADO-EKITI GEOTHERMAL GRADIENT CONTOUR MAP

3.1.7. DATA INTERPRETATION FOR ADO-EKITI HEAT FLOW MAP

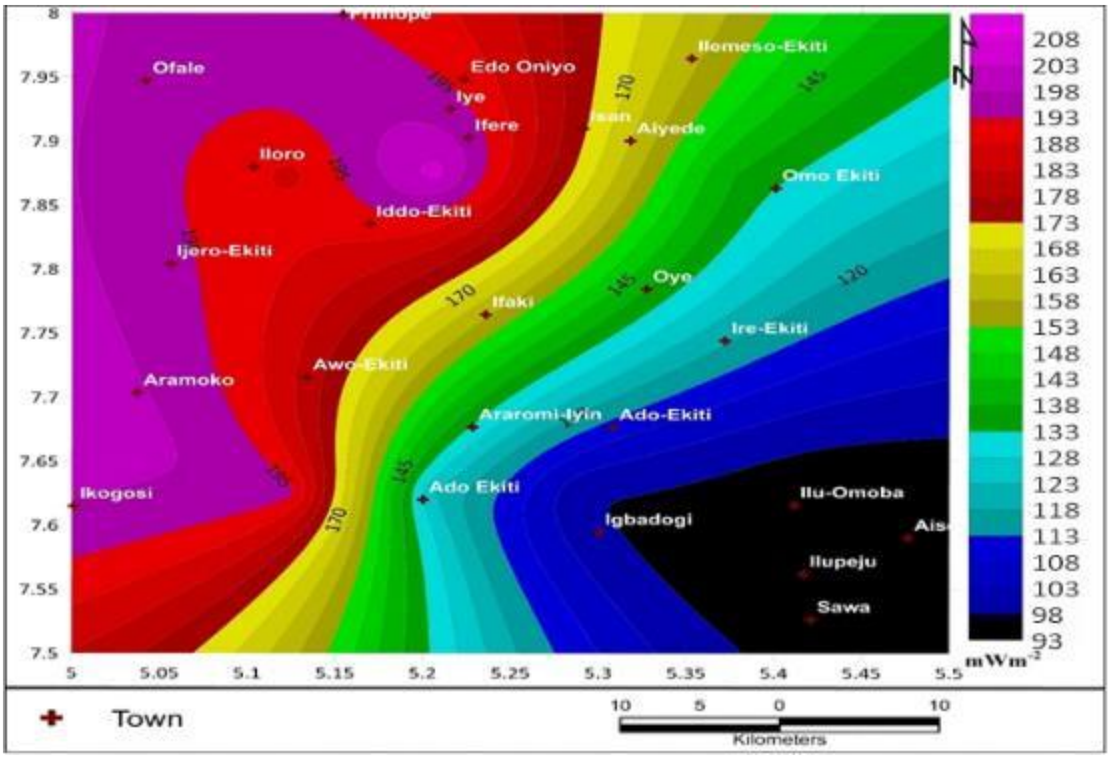

Figure 11 ADO-EKITI HEAT FLOW MAP

The Specific areas within Ado-Ekiti, particularly in the southern and eastern parts, exhibit higher heat flow values, indicating potential geothermal hotspots. Heat flow varies within the region, highlighting the importance of targeted exploration efforts. The city itself is situated within an area of moderate heat flow, which could potentially support geothermal direct-use applications. Warm Colors (Reds, Oranges, Yellows): Represent higher heat flow values, indicating areas with greater heat escaping from the Earth's interior. These areas are typically of higher interest for geothermal exploration due to the potential for higher subsurface temperatures. Cool Colors (Blues, Greens) Indicate lower heat flow values, suggesting less heat escaping from the Earth's interior. While not devoid of potential, these areas are generally less promising for geothermal development. The provided heat flow map for Ado-Ekiti reveals variations in heat flow across the region. The presence of areas with notably high heat flow values suggests promising prospects for geothermal exploration and development. The heat flow values on the map are represented by contour lines with values ranging from 93 to 208. The unit of measurement for heat flow is mW/m^2 (milliwatts per square meter).

3.1.8. Data interpretation for ado-ekiti total magnetic intensity map

The map in Figure 17 reveals several magnetic anomalies of varying intensities and extents across the Ado-Ekiti region, suggesting diverse subsurface geology. Areas with high magnetic intensity gradients, particularly those associated with circular or linear features, could indicate potential geothermal targets such as intrusive bodies or fault zones, which often act as conduits for geothermal fluids. Warm Colors (Reds, Oranges, and Yellows) Represent higher total magnetic intensity values, indicating areas with stronger magnetic anomalies. These areas often correspond to subsurface geological structures like igneous intrusions, which can be associated with geothermal activity. Cool Colors (Blues, Greens)Represent lower total magnetic intensity values, indicating areas with weaker magnetic anomalies. These areas are typically associated with sedimentary rocks, which may have lower geothermal potential. The total magnetic intensity values on the map range from approximately 32800 nT to 33200 nT. The unit of measurement is nanoTeslas (nT). The total magnetic intensity map provides valuable insights into the subsurface geology of the Ado-Ekiti region, which can indirectly inform geothermal exploration. Areas with pronounced magnetic anomalies, especially those characterized by sharp gradients or closures, warrant further investigation.

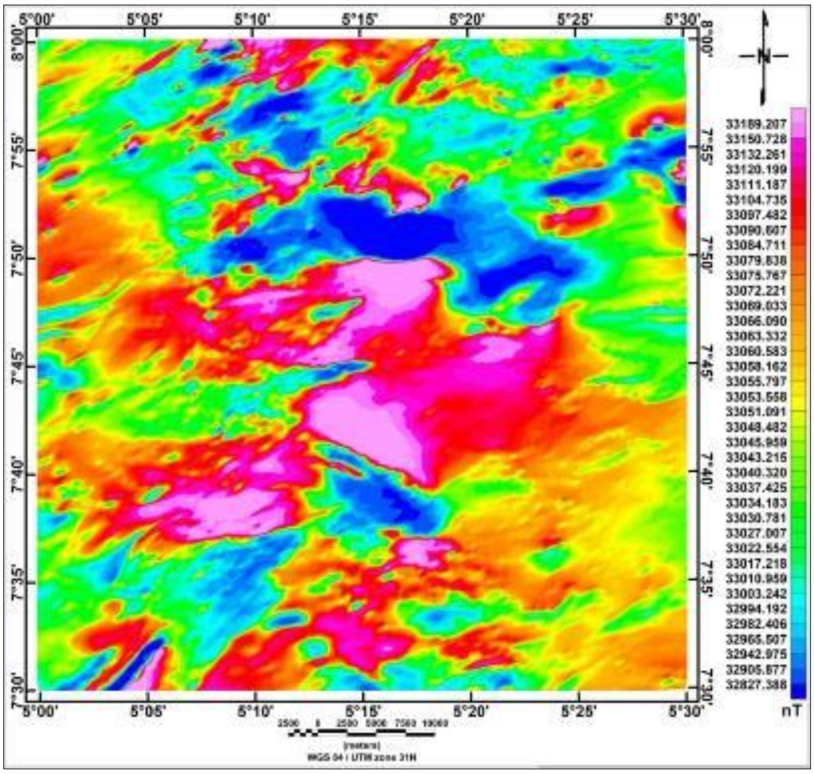

Figure 12 ado-ekiti total magnetic intensity map

3.1.9. Data interpretation for ado-ekiti residual magnetic anomaly map

The map reveals several residual magnetic anomalies of varying intensities and extents across the Ado-Ekiti region, suggesting diverse subsurface geology. Areas with high residual magnetic anomaly gradients, particularly those associated with circular or linear features, could indicate potential geothermal targets such as intrusive bodies or fault zones, which often act as conduits for geothermal fluids. Warm Colors (Reds, Oranges, Yellows) Represent positive residual magnetic anomalies, indicating areas with stronger magnetic variations from the regional field. These areas often correspond to subsurface geological structures like igneous intrusions, which can be associated with geothermal activity. Cool Colors (Blues, Greens) Represent negative residual magnetic anomalies, indicating areas with weaker magnetic variations from the regional field. These areas are typically associated with sedimentary rocks, which may have lower geothermal potential. The residual magnetic anomaly map provides valuable insights into the subsurface geology of the Ado-Ekiti region, which can indirectly inform geothermal exploration. Areas with pronounced magnetic anomalies, especially those characterized by sharp gradients or closures, warrant further investigation. The residual magnetic anomaly values on the map range from approximately -206.617 nT to 144.533 nT. The unit of measurement is nanoTeslas (nT).

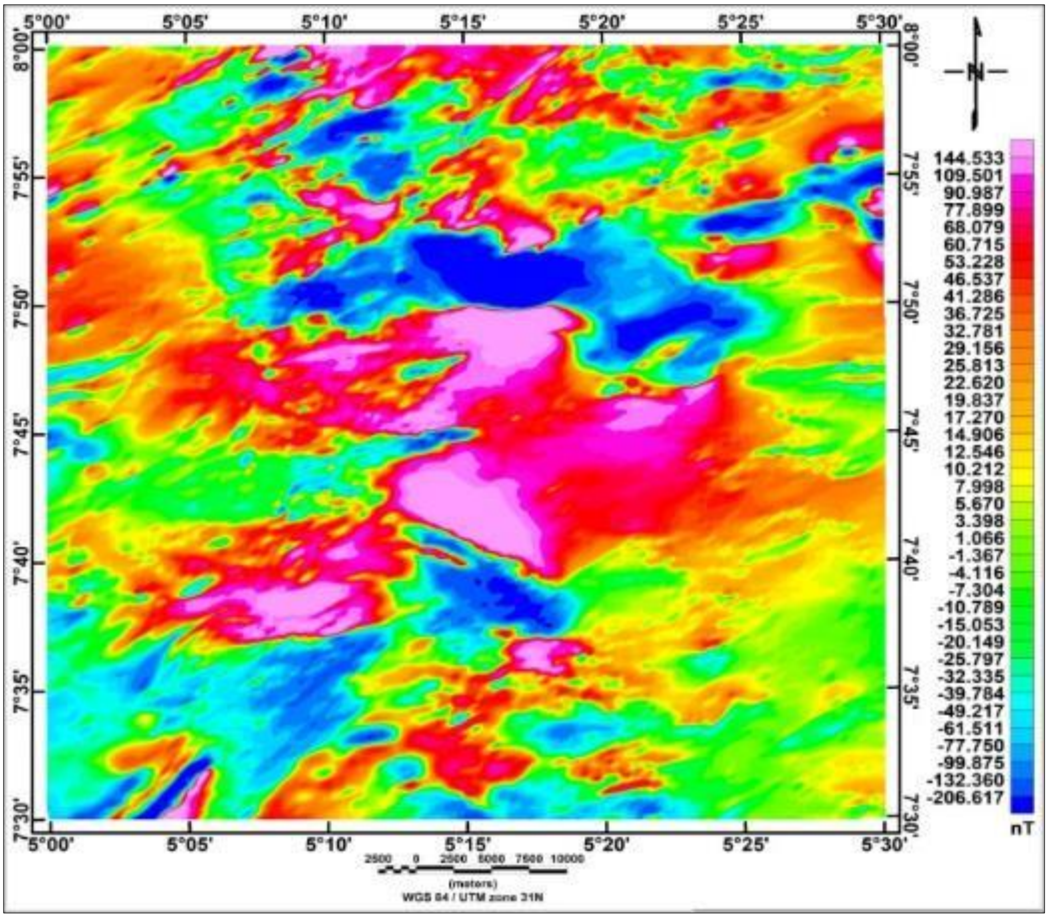

Figure 13 ado-ekiti residual magnetic anomaly map

4. Discussion

Similarities between the Geothermal Potential of Ijebu Igbo and Ado-Ekiti Regions. Both regions have been analyzed using various geophysical maps, including depth estimation, geothermal gradient, heat flow, total magnetic intensity, and residual magnetic anomaly maps. These analyses provide valuable insights into the geothermal potential of the areas, and a comparative discussion reveals several common features that underscore the regions' geothermal promise.

4.1. Geothermal Gradient and Heat Flow

One of the most significant similarities between the Ijebu Igbo and Ado-Ekiti regions is the observed geothermal gradients and heat flow patterns. Both regions exhibit areas with notably high geothermal gradients and elevated heat flow values, which are key indicators of geothermal potential.

- Geothermal Gradient: In both Ijebu Igbo and Ado-Ekiti, the geothermal gradient maps reveal regions with high-temperature increases per unit depth. Specifically, both regions have zones where the geothermal gradient exceeds typical regional values, indicating that subsurface temperatures rise more quickly with depth in these areas. This similarity suggests that both regions may possess subsurface conditions conducive to geothermal energy production.

- Heat Flow: Similarly, the heat flow maps of both regions show areas with elevated heat flow values. In Ijebu Igbo, the central and southern parts exhibit higher heat flow, while in Ado-Ekiti, the southern and eastern regions display similar characteristics. These areas are marked by warm colors on the heat flow maps, suggesting that significant amounts of heat are escaping from the Earth's interior, which is a promising sign for geothermal exploration.

4.2. Subsurface Geology and Magnetic Anomalies

Another area of similarity lies in the subsurface geology, as indicated by the total magnetic intensity and residual magnetic anomaly maps of both regions. These maps provide clues about the distribution of rock types and potential geothermal targets such as igneous intrusions or fault zones.

- Total Magnetic Intensity: In both regions, the total magnetic intensity maps reveal areas with higher magnetic intensities, which are often associated with igneous and metamorphic rocks. These rock types are typically linked to tectonic activities and potential heat sources for geothermal systems. The presence of such rocks in both Ijebu Igbo and Ado-Ekiti suggests a similar geological setting that could favor geothermal activity.
- Residual Magnetic Anomalies: The residual magnetic anomaly maps for both regions show areas with pronounced magnetic anomalies, particularly those characterized by sharp gradients or closures. These anomalies may indicate the presence of intrusive bodies or fault zones, which can act as conduits for geothermal fluids. The similar patterns observed in both regions imply that they may share comparable subsurface geological structures that are conducive to geothermal activity.

4.3. Depth Estimation and Curie Point Depth

The depth estimation and Curie point depth analyses provide additional evidence of similarities between the two regions.

- Depth Estimation: In both Ijebu Igbo and Ado-Ekiti, depth estimation maps reveal variations in subsurface depth that correlate with geothermal potential. Areas with deeper subsurface features, as indicated by darker colors, are often associated with higher geothermal gradients and heat flow values. The similar depth profiles in both regions suggest that they may share analogous geothermal characteristics at varying depths.
- Curie point Depth: The Curie point depth analysis, conducted for the Ado-Ekiti region and partially inferred for Ijebu Igbo, shows that both regions have areas where the Curie point is relatively shallow. A shallower Curie point depth typically correlates with higher heat flow, which is a favorable condition for geothermal exploration. This similarity further reinforces the idea that both regions possess comparable geothermal potential.

4.4. Geothermal Exploration Potential

The similarities in geothermal gradient, heat flow, subsurface geology, and depth estimation between the Ijebu Igbo and Ado-Ekiti regions suggest that both areas have promising geothermal exploration potential. The presence of high geothermal gradients and elevated heat flow, combined with favorable subsurface geological structures, indicates that both regions could be viable candidates for geothermal energy development.

While there are certainly differences in the specific geophysical characteristics of each region, the overarching similarities suggest that the geothermal potential of Ijebu Igbo and Ado-Ekiti should be further explored. Both regions may benefit from targeted geothermal exploration efforts that take into account the common features identified in this analysis.

In conclusion, the comparative analysis of the Ijebu Igbo and Ado-Ekiti regions reveals several similarities that highlight their potential for geothermal energy development. Both regions exhibit key geophysical indicators, such as high geothermal gradients, elevated heat flow, and favorable subsurface geology that are critical for successful geothermal exploration. These findings suggest that continued exploration in these areas could lead to the identification and development of significant geothermal resources, contributing to sustainable energy solutions in the region.

5. Conclusion

The aeromagnetic data of Ijebu-Ife_ (Sheet 281) was subjected to spectral analysis to access the geothermal potential of the study area and environs. The Curie point depth values range from (13.10- 22.30) km, the geothermal gradient values range from (25.01 - 37.123) ° C/km and the heat flow values range from (68.736- 108.079) mW/m2. The SE edge, Abigi, Agbure, and Ilyushin host the highest values of heat flow and geothermal gradient with corresponding shallowest values of curie point depth (Fig. 4.2 a-c). Regions like Omo, Oso, Kojala, and Oniparaja also have good geothermal manifestations. Generally, for a viable geothermal reservoir, a heat flow range of (80 - 100) mW/m2is recommended, hence it can be inferred that every region in the study area could be considered as having good prospects except within the Northern region, Gbamu of the study area with low heat flow below 80 mWm-2.

Ikogosi was found to be underlain by three rock units; quartz schist, quartz mica schist, and quartzite. At the basal part of the spring where the cold and hot springs meet, the quart mica schist covers the area. The particles of mica and quartz are quite small. Moving upward the outcrop of the Ikogosi warm spring, the quartz grains become coarse and coarser grains until they eventually become quartz minerals.

The aeromagnetic data of Ado-Ekiti (Sheet 244) was subjected to spectral analysis to access the geothermal potential of the study area and environs. The Curie point depth values range from (6.89- 16.15) km, the geothermal gradient values range from (39.2– 84.74) ° C/km and the heat flow values range from (96.05- 207.31) mW/m2 (Figs. 4-1 a-c). The NW edge covering Ofale, Iye, Ifere, Iddo-Ekiti, Ijero-Ekiti, Aramoko, and Ikogosi hosts the highest anomalous values of heat flow and geothermal gradient with corresponding shallowest values of Curie point depth (Fig. 4.2 a-c). Generally, for a viable geothermal reservoir, a heat flow range of 80 to 100 mW/m2is recommended, hence it can be inferred that every region in the study area could be considered as having a good prospect of the study area with high heat flow above 80 – 100 mWm^{-2}

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declared that there is no conflict of interest.

References

[1] **Aigbedion, I., & Salufu, S. O. (2023).** Geothermal assessment of Farin Ruma. *Journal of Geoscience,* 21-30.

[2] **Aigbedion, I., Salufu, S. O., Aikhuelo, D. O., & Aigbedion, E. (2023).** Innovative geothermal assessment of Akiri, Nassarawa State. *Journal of Insight and Mining Engineering,* 50-65.

[3] **Ashissh Kumar, K., & Md Mijanur Rahman. (2020).** Exploration and corrective measures of greenhouse gas emission from fossil fuel power stations for Bangladesh. *Journal of Cleaner Production, 244,* 118645. https://doi.org/10.1016/j.jclepro.2019.118645

[4] **Bhattacharyya, B. K. (1966).** Continuous spectrum of the total-magnetic-field anomaly due to a rectangular prismatic body. *Geophysics, 31(1),* 97-121. https://doi.org/10.1190/1.1439779

[5] **Bracewell, R. N. (1989).** The Fourier transform. *Scientific American, 260(6),* 86-95. https://doi.org/10.1038/scientificamerican0689-86

[6] **Connard, G., Couch, R., & Gemperle, M. (1983).** Analysis of aeromagnetic measurements from the Cascade Range in central Oregon. *Geophysics, 48(3),* 376-390. https://doi.org/10.1190/1.1441488

[7] **Grauch, R. I. (2002).** Rare earth element mines, deposits and occurrences (Vol. 2, No. 189). *US Department of the Interior, US Geological Survey.*

[8] **Huttrer, G. W. (2001).** The status of world geothermal power generation 1995–2000. *Geothermics, 30(1),* 1-27. https://doi.org/10.1016/S0375-6505(00)00034-8

[9] **International Energy Agency. (2021).** Global energy review: CO2 emissions in 2021. *IEA.*

[10] **Kearey, P. (2002).** *An introduction to geophysical exploration* (Vol. 4). John Wiley & Sons.

[11] **Lowrie, W. (1997).** *Fundamentals of geophysics.* Book Fi org.

[12] **Manzella, A. (2017).** Geothermal energy: A reliable and efficient renewable resource. *Renewable Energy Journal.*

[13] **Porkhial, M. (2015).** 3-D simulation of heat transfer rate in geothermal pile-foundation heat exchangers with spiral pipe configuration. *Applied Thermal Engineering, 87,* 655-668. https://doi.org/10.1016/j.applthermaleng.2015.05.049

[14] **Represas, P. (2013).** Interpretation of gravity data to delineate structural features connected to low-temperature geothermal resources at Northeastern Portugal. *Journal of Applied Geophysics, 92,* 30-38. https://doi.org/10.1016/j.jappgeo.2013.02.011

[15] **Smith, L. I. (2002).** A tutorial on principal components analysis. https://doi.org/10.1.1.116.3501

[16] **Spector, A., & Grant, F. S. (1970).** Statistical models for interpreting aeromagnetic data. *Geophysics, 35(2),* 293-302. https://doi.org/10.1190/1.1440092

[17] **Stacey, F. D., & Loper, D. E. (1988).** Thermal history of the Earth: A corollary concerning non-linear mantle rheology. *Physics of The Earth and Planetary Interiors, 53(1-2),* 167-174. https://doi.org/10.1016/0031-9201(88)90092-6

[18] **Vijay, A., Kumar, A., & Rahman, A. (2015).** Genomics and the challenging translation into conservation practice. *Trend Reviews Journal, 30(2),* 78-87. https://doi.org/10.1016/j.tree.2014.11.009