



## OPEN Investigation of low enthalpy geothermal resources in the transitional geological environment: a pathway to Nigeria's Sustainable Development Goals achievement

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Nigeria faces a significant energy deficit (61.2% electricity access), hindering progress toward SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Despite geothermal potential, comprehensive assessments of low-enthalpy resources (that is, subsurface temperatures below 100 °C) in transitional geological environments (TGEs) — basement-sedimentary contact zones with mixed conductive-advective heat transfer — remain underexplored. This study uses high-resolution aeromagnetic data interpretation with statistical modeling to delineate geothermal potential within the Egbako-Share axis of North-Central, Nigeria. Spectral analysis adopting centroid depth technique from 40 overlapping blocks was employed to estimate Curie Point Depths (CPD), geothermal gradients (GTG), and heat flow (HF). Statistical modeling — including correlation analysis, multiple regression, PCA, and spatial autocorrelation (Moran's I, Getis-Ord Gi\*) — provided a robust framework for resource assessment and risk evaluation. The analysis revealed significant geothermal resources with CPD ranging from 26 to 46 km (mean:  $38 \pm 6$  km), GTG of 13–23 °C/km (mean:  $16 \pm 2$  °C/km), and HF values of 31–57 mW/m<sup>2</sup> (mean:  $39 \pm 6$  mW/m<sup>2</sup>). Strong negative correlations between CPD and both GTG ( $r = -0.892$ ,  $p < 0.001$ ) and HF ( $r = -0.891$ ,  $p < 0.001$ ) were established, with the regression model explaining 79.5% of HF variance. PCA identified 12 high-potential geothermal zones for low-enthalpy development. Under a conceptual scenario assuming full development of all 12 zones, modelled capacity could range from approximately 15 to 25 MW, with scenario-based annual CO<sub>2</sub> emission reductions of 85,000–140,000 t/year (subject to confirmatory drilling and feasibility studies), supporting Nigeria's SDG 7, SDG 13, and related development targets.

**Keywords** Geothermal Energy, Statistical Modeling, Spectral Analysis, Sustainable Development Goals, Renewable Energy, Transitional Geological Environment

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The global transition toward sustainable energy systems has intensified the search for renewable energy resources, with geothermal energy emerging as a reliable baseload power source capable of supporting economic development while minimizing environmental impact. Nigeria, Africa's most populous nation with about 227.9 million inhabitants in 2023, faces significant energy challenges with only 61.2% of the population having access to electricity<sup>1</sup>. This deficit, driven by over-reliance on fossil fuels and insufficient grid capacity, substantially impedes progress toward UN Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), and underscores the urgency of diversifying into indigenous renewable resources such as geothermal energy.

Against this backdrop, geothermal energy (and specifically the low-enthalpy resources accessible in intracratonic sedimentary settings) represents a strategically important and underexplored option for North-Central (NC) Nigeria. Recent advances in geothermal play-type classification have extended these frameworks to sedimentary intracratonic settings where conduction-dominated heat transfer prevails, a geological context directly applicable to the Bida Basin<sup>2</sup>. Similarly, regional assessments of low-enthalpy potential in Sub-Saharan intracratonic basins have demonstrated that even modest geothermal gradients of 25–35 °C/km within Mesozoic and Cretaceous sedimentary sequences can support economically viable ground-source heating applications<sup>3</sup>.

Geothermal energy represents a largely underexplored renewable resource in Nigeria, despite its significant potential. Previous studies have indicated varying geothermal prospects across different geological terrains within the country. For instance, investigation in the Benue Trough<sup>4</sup> has revealed regions with high heat flow and shallow Curie Point depth (CPD). The Bida Basin, a major intracratonic sedimentary basin in NC Nigeria, presents favourable radiogenic geological conditions for geothermal exploration due to its complex structural framework and proximity to the Younger Granite complexes. The basin's geological setting, characterized by Cretaceous sedimentary sequences overlying and surrounded by Precambrian basement rocks, provides potential pathways for geothermal fluid circulation<sup>5,6</sup>. Although these prior works established a foundational understanding, a critical gap persists in providing a comprehensive, integrated assessment of geothermal resources within transitional geological environments (TGEs).

In this study, TGEs are tectonically influenced geological zones or unconformity at the boundary of crystalline basement complexes and sedimentary basins (that is, intracratonic rift systems or basin-margin contact zones) where heat transfer occurs via both conductive diffusion through rock and advective fluid migration through permeable pathways. These are distinct from stable cratons (thick cold lithosphere, geothermal gradients < 15 °C/km) and oceanic settings (thin crust, high heat flow > 100 mW/m<sup>2</sup>). “Low-enthalpy” resources are defined as subsurface temperatures below 100 °C<sup>7,8</sup>, enabling direct-use applications: district heating networks, agricultural drying, aquaculture, and ground-source heat pump systems. This threshold precludes conventional steam electricity generation but is commercially proven in comparable transitional settings (e.g., Pannonian Basin, Vienna Basin, Turkish Neogene grabens). This clarification is essential for non-specialist readers to appreciate the scale, technology requirements, and economic model of the proposed development pathway.

Recent advances in geophysical data processing and statistical modelling have enhanced the ability to assess geothermal resources quantitatively. Aeromagnetic data, when processed using spectral analysis techniques, provides valuable insights into subsurface thermal conditions through the estimation of CPD, which represent the depth at which magnetic minerals lose their ferromagnetic properties due to elevated temperatures. These parameters serve as proxies for geothermal gradient estimation and heat flow calculations<sup>9</sup>. The application of advanced statistical methods, including multivariate analysis, correlation studies, and predictive modelling, enables comprehensive resource assessment and risk evaluation for geothermal development<sup>10</sup>. Such approaches are essential for evidence-based decision-making in renewable energy planning, particularly in low and middle-income countries where resource allocation efficiency is critical.

This study addresses the aforementioned research gap by offering a novel and integrated approach to geothermal resource assessment in the Egbako-Share axis of North-Central Nigeria. The innovation lies in the synergistic application of high-resolution aeromagnetic data interpretation with a comprehensive suite of advanced statistical modeling techniques, including multivariate analysis, correlation studies, predictive modeling, Principal Component Analysis (PCA), and robust uncertainty assessment. This integrated methodology allows for more precise delineation of geothermal potential, development of predictive models, and robust evaluation of resource viability for low-enthalpy applications, which have been less systematically

characterised in this specific transitional geological setting. The study aims to move beyond basic geothermal parameter estimation to provide insights for sustainable energy planning and risk evaluation.

The primary objectives of this study are to: (1) conduct comprehensive statistical analysis of geothermal parameters derived from aeromagnetic data; (2) develop robust predictive models for geothermal resource assessment; (3) identify and delineate high-potential zones for sustainable low-enthalpy geothermal development; (4) evaluate the direct and indirect contributions of geothermal energy to Nigeria's SDG achievement; and (5) provide data-driven recommendations for future exploration and development strategies. The study area is underlain by the crystalline basement rocks and sedimentary rocks of Bida Basin. Effectively harnessing geothermal energy could significantly contribute to the national energy portfolio, particularly by strengthening the national electric grid, and would contribute additionally to SDGs 8 (Economic Growth), 9 (Innovations) and 11 (Sustainable Cities).

It is important to acknowledge certain limitations inherent in this reconnaissance-level study. The estimation of geothermal gradients and heat flow relies on the assumption of a uniform thermal conductivity value ( $2.5 \text{ Wm}^{-1}\text{C}^{-1}$ , average for igneous rocks) and a single Curie temperature ( $580^\circ\text{C}$ , for magnetite) across the entire study area, since both terrains are integral of the reactivated crystalline rocks of West Africa with diverse thicknesses<sup>11,12</sup>. Effects of other magnetic minerals or variations in rock thermal conductivity, particularly in sedimentary sequences, are assumed to be minimal since magnetite is readily available in Nigerian crust<sup>13</sup>. Future studies could incorporate sensitivity analyses or localised thermal property measurements to refine these estimations and reduce uncertainty.

### Geological and geographical setting of the study area

The study area spans approximately  $18,150 \text{ km}^2$  within two NC states: Kwara and Niger. It is geographically bounded between latitudes  $8^\circ 30'\text{N}$  to  $9^\circ 30'\text{N}$  and longitudes  $4^\circ 30'\text{E}$  to  $6^\circ 00'\text{E}$ . Share, Lafiagi, Patigi, and the western part of Jebba fall in Kwara State, while Mokwa, Egbako, and the eastern part of Jebba fall in Niger State.

Geologically, the Kwara segment lies within the Precambrian Basement Complex (Fig. 1a), which dominates nearly half of Nigeria's landmass<sup>12</sup>. This terrain comprises diverse igneous and metamorphic rocks, mainly older granites, younger granites, granite-gneiss, and migmatite-gneiss. These rock types often form prominent outcrops above the surrounding peneplain. Older granites typically appear as isolated dome-shaped exposures, while younger granites form ring complexes containing biotite and soda pyroxenes, often associated with dioritic mafic intrusions. Granite-gneiss in the area is commonly light-coloured with grey-green hues. The region also hosts economically valuable mica and gemstones, and migmatitic rocks are increasingly utilised as construction aggregates<sup>14</sup>.

The Niger State portion lies within the Bida Basin (Fig. 1a and b), a northwest-to-southwest-trending intracratonic sedimentary basin extending from Kontagora in Niger State to areas beyond Lokoja, comprising

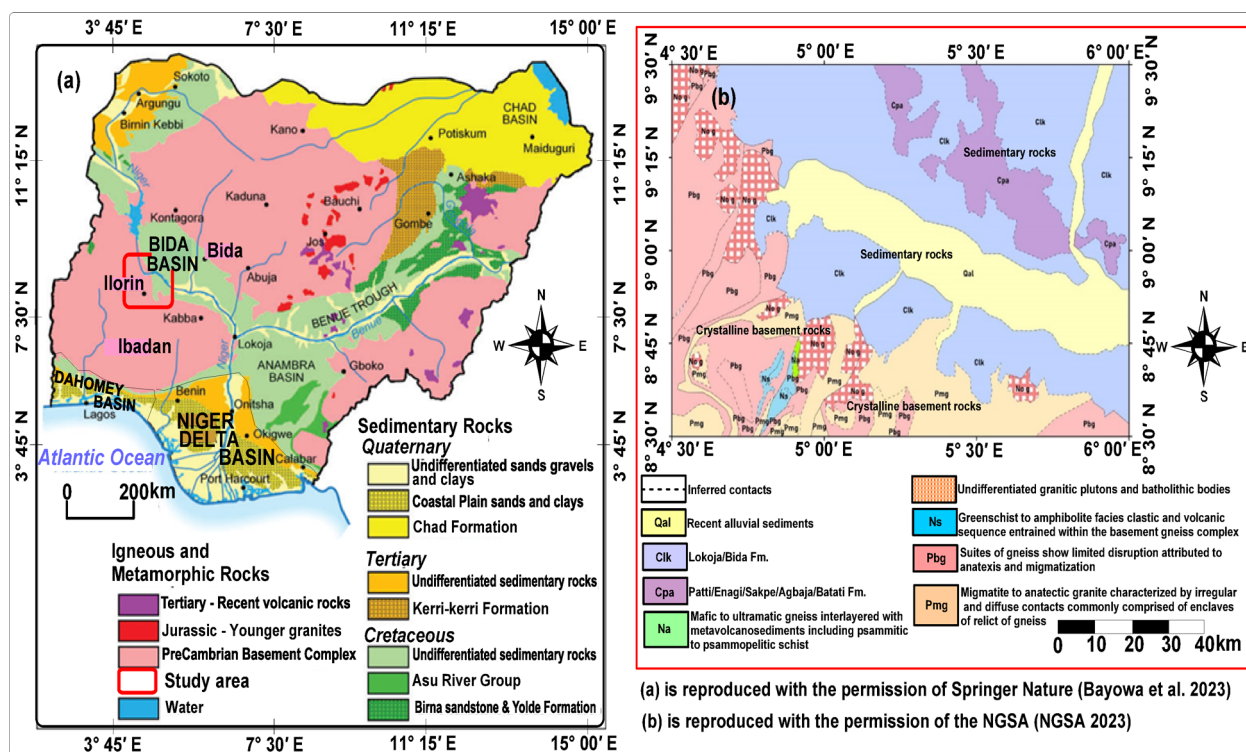


**Fig. 1.** (a). Geological map of Nigeria showing the study location within the NC (Adapted from Bayowa et al.<sup>20</sup>); (b). Geological and litho-structural map of the SW crystalline basement-sedimentary rocks of Bida Basin in the NC (Adapted from NGSA<sup>21</sup>).

the Batati, Agbaja, Lokoja, Patti, and Enagi formations<sup>15</sup>. These Campanian–Maastrichtian strata record a transition from marine to fluvial depositional environments. The sedimentary sequence attains a thickness of approximately 3 km. The litho-structural features are presented in Fig. 1b.

Heat transfer in the crust occurs primarily by conductive diffusion, but in the Bida Basin's sedimentary settings, advective transport via groundwater flow through permeable aquifers also contributes significantly<sup>16</sup>. Lateral and vertical heat flow variations are attributed to forced convective processes driven by fluid migration<sup>42</sup>. These dual-mode heat transfer dynamics are particularly important in TGEs where basement–sediment interfaces create pathways for thermally buoyant fluid upwelling, a mechanism whose quantification has been advanced in recent three-dimensional numerical modelling studies of comparable intracratonic basin settings<sup>17</sup>.

The geological and thermal framework described above has been the subject of several prior geophysical investigations, but significant gaps remain that this study is specifically designed to address. Aeromagnetic-based CPD studies within the broader NC Nigeria region have been conducted by Nwankwo et al.<sup>6</sup>, who estimated Curie depths and heat flow across the Benue Trough, and by Alhassan et al.<sup>18</sup> and Salaudeen et al.<sup>19</sup>, who applied spectral analysis to aeromagnetic data over portions of the Bida Basin. These works established that the basin exhibits deeper-than-average CPDs (typically 30–45 km) and correspondingly subdued geothermal gradients relative to more tectonically active Nigerian terrains, and identified the basin's low-enthalpy character. However, they share three critical limitations: (i) their spatial coverage was either basin-wide at coarse resolution or limited to sub-areas excluding the Egbako–Share transitional axis where basement–sediment interfacing is most pronounced; (ii) none applied multivariate statistical methods—such as PCA, spatial autocorrelation (Moran's I), or Getis–Ord Gi\* hotspot delineation—to systematically rank and spatially cluster high-potential zones from derived thermal parameters; and (iii) none integrated quantified uncertainty propagation or risk evaluation into resource estimates. The present study advances beyond these prior works by applying high-resolution spectral analysis across 40 overlapping aeromagnetic blocks specifically covering the Egbako–Share axis, combining the derived CPD, GTG, and HF outputs with a comprehensive statistical framework to produce the first spatially explicit, statistically validated delineation of low-enthalpy geothermal hotspots in this TGE. This methodological integration—combining CPD-based thermal parameter estimation with robust multivariate spatial statistics—constitutes the principal novelty of the study relative to all preceding geothermal assessments in the Bida Basin and NC Nigeria.

## Materials and methods

### Data acquisition and processing

Total-field aeromagnetic data for the study areas — Jebba–Mokwa–Egbako (Sheets 181–183) in Niger State and Share–Lafiagi–Pategi (Sheets 202–204) in Kwara State — were acquired during high-resolution airborne surveys conducted by Fugro Airborne Surveys Limited on behalf of the Nigerian Geological Survey Agency (NGSA) between 2005 and 2009<sup>22</sup>. A fixed-wing aircraft equipped with a cesium-vapour magnetometer (sensitivity  $\approx 0.001$  nT; sampling rate: 10 Hz) maintained a mean terrain clearance of 80 m above ground level (AGL) via radar altimetry, employing drupe flying over the study area's terrain, which ranges from approximately 50 m to 450 m above mean sea level. Primary flight lines were oriented at an azimuth of 135° (SE–NW), perpendicular to the dominant NE–SW structural grain of the Basement Complex to maximise anomaly contrast, while tie lines ran at 45° (NE–SW). Flight-line and tie-line spacings were 500 m and 2,000 m respectively, yielding a 4:1 ratio that meets the recommended maximum of 5:1 for effective cross-line levelling<sup>22</sup>. The 500 m line spacing resolves a Nyquist wavelength of 1,000 m, sufficient to detect anomalies associated with basement structures and thermomagnetic sources at target depths of 1–5 km.

Aircraft positioning was controlled by a differential GPS (dGPS) receiver in real-time kinematic (RTK) mode, achieving horizontal and vertical accuracies better than  $\pm 3$  m and  $\pm 5$  m respectively. The TMI was recorded continuously at 10 Hz, yielding an along-track sample interval of approximately 6.7 m at the survey ground speed of 240 km/h. Field data delivered in Oasis Montaj™ XYZ format, where x and y denote geographic easting and northing in Universal Transverse Mercator (UTM) Zone 32 N coordinates (WGS84 datum), and z represents the TMI value in nanotesla (nT). All processing was performed in Geosoft Oasis Montaj. The 12th-generation International Geomagnetic Reference Field (IGRF-12, degree and order  $n = 13$ ) was subtracted at the survey epoch (2005–2009) to isolate the crustal anomaly field. A micro-levelling decorrelation filter with a cut-off wavelength of 4,000 m (twice the tie-line spacing) was applied to suppress residual heading errors and diurnal drift. The corrected total-field anomaly data were then gridded at a 100 m cell size using a minimum-curvature algorithm<sup>23</sup>.

Regional field separation was achieved by fitting and subtracting a second-order polynomial trend surface from the gridded total-field anomaly, yielding the residual magnetic intensity (RMI). Because the study area lies within a low-magnetic-latitude zone (approximately 8°–10°N), where the conventional reduction-to-pole (RTP) operator is numerically unstable, a reduction-to-equator (RTE) filter was applied instead<sup>24</sup>. The RTE filter was computed in the two-dimensional wavenumber domain via Fast Fourier Transform (FFT), with a Hanning taper on the outer 10% of the grid to suppress edge effects, and was parameterised using the ambient IGRF-12 inclination ( $I \approx -3^\circ$  to  $-5^\circ$ ) and declination ( $D \approx -1^\circ$  to  $0^\circ$ ) for the survey epoch. This filter repositions anomalies directly above their causative sources and symmetrises anomaly shapes, providing an enhanced RMI grid suitable for spectral analysis and CPD estimation.

### Method of estimating geothermal parameters in the study area

Spectral analysis, using the centroid method, was carried out on the enhanced RMI data to estimate CPD, geothermal gradient (GTG), and heat flow (HF). The full spectral analysis models are detailed in Supplementary Material (SM1).

The RTE RMI map (Fig. 2) was divided into 40 overlapping spectral blocks (Fig. 3), each spanning  $37 \times 37$  km, consistent with Usman et al.<sup>25</sup>. This block dimension is justified on three independent grounds. First, the Shuey et al.<sup>26</sup> criterion establishes that the spectral method cannot reliably resolve magnetic source bodies whose bases lie deeper than the window length divided by  $2\pi$ ; for a 37 km window, this yields a practical CPD upper limit consistent with the study's observed CPD range of 26–46 km. Second, Akbar and Fathianpour<sup>27</sup> demonstrated through synthetic forward modelling that blocks in the 30–40 km range optimise the trade-off between spatial resolution and spectral completeness for CPDs in the target range. Third, Núñez Demarco et al.<sup>28</sup> recommend a minimum window width of at least  $2\pi$  times the target depth; the 37 km blocks satisfy this for the centroid step ( $Z_0$ ), while the basal depth is derived as  $Z_b = 2Z_0 - Z_t$ <sup>29</sup>.

The centroid method resolves  $Z_0$  from the low-wavenumber slope and  $Z_t$  from the intermediate-to-high wavenumber portion of the radially averaged power spectrum, with CPD derived as  $Z_b = 2Z_0 - Z_t$ <sup>29</sup>. A critical limitation is that centroid depths are reliably estimated only where  $n < 0.05$  rad/km (wavelengths  $> 125$  km); errors in wavenumber range assignment can introduce CPD errors exceeding 40 km<sup>28</sup>. For this study—with CPDs of 26–46 km and a 37 km block—the method operates near its practical resolution limit for the deepest blocks. The resulting CPD estimates carry an inherent uncertainty of approximately  $\pm 5$ –8 km (consistent with bootstrap confidence intervals in Table 1), and should be interpreted as reconnaissance-level indicators of crustal thermal structure rather than precise pointwise depths. The  $37 \text{ km} \times 50\%$  overlap configuration represents a practical compromise calibrated to the survey area dimensions ( $\sim 220 \text{ km} \times 180 \text{ km}$ ) and the target CPD range.

Each spectral block underwent average power spectrum analysis using the MAGMAP program within Geosoft Oasis Montaj. A Python script was used to plot the logarithm of spectral energies against wavenumbers: higher wavenumbers correspond to shallow sources, lower wavenumbers to deeper anomalous bodies<sup>25</sup>, and the high-wavenumber tail is interpreted as noise. Depths to the top, centroid, and bottom of magnetic sources were determined from the slopes of these log-energy vs. wavenumber curves via FFT transformation. The depth to the bottom of magnetic sources was interpreted as the CPD, from which GTG and HF were subsequently derived, and contour maps of all three parameters were generated.

A thermal conductivity value of  $2.5 \text{ W m}^{-1}\text{C}^{-1}$  and a Curie temperature of  $580^\circ\text{C}$  (magnetite) were adopted as standard reference values, consistent with the igneous and crystalline rock mean reported by Clauser and Huenges<sup>30</sup>, who documented that plutonic and metamorphic rocks typically range from 1.7 to  $3.5 \text{ W m}^{-1}\text{K}^{-1}$ . Three sensitivity scenarios were evaluated: (i) lower-bound  $\sigma = 1.5 \text{ W m}^{-1}\text{C}^{-1}$ , representative of Cretaceous shale and sandstone sequences of the Batati, Agbaja, and Lokoja Formations<sup>5,6,13</sup>, for which Clauser and Huenges<sup>30</sup> report typical conductivities of  $1.0$ – $2.0 \text{ W m}^{-1}\text{K}^{-1}$ ; (ii) baseline  $\sigma = 2.5 \text{ W m}^{-1}\text{C}^{-1}$  (igneous/crystalline average<sup>14</sup>); and (iii) upper-bound  $\sigma = 3.5 \text{ W m}^{-1}\text{C}^{-1}$ , consistent with the Precambrian crystalline basement<sup>13,25</sup>.

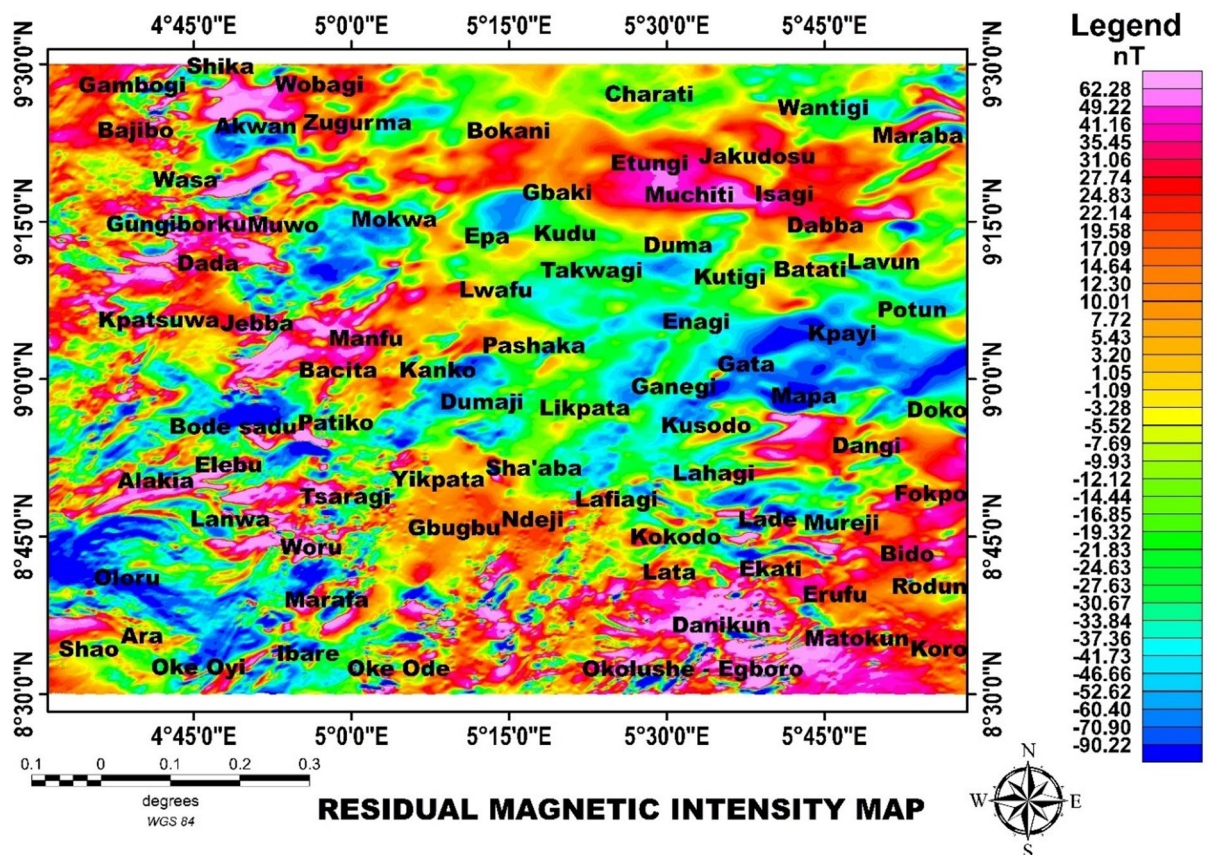


Fig. 2. The RTE RMI map of the study area, illustrating variations in magnetic signatures.

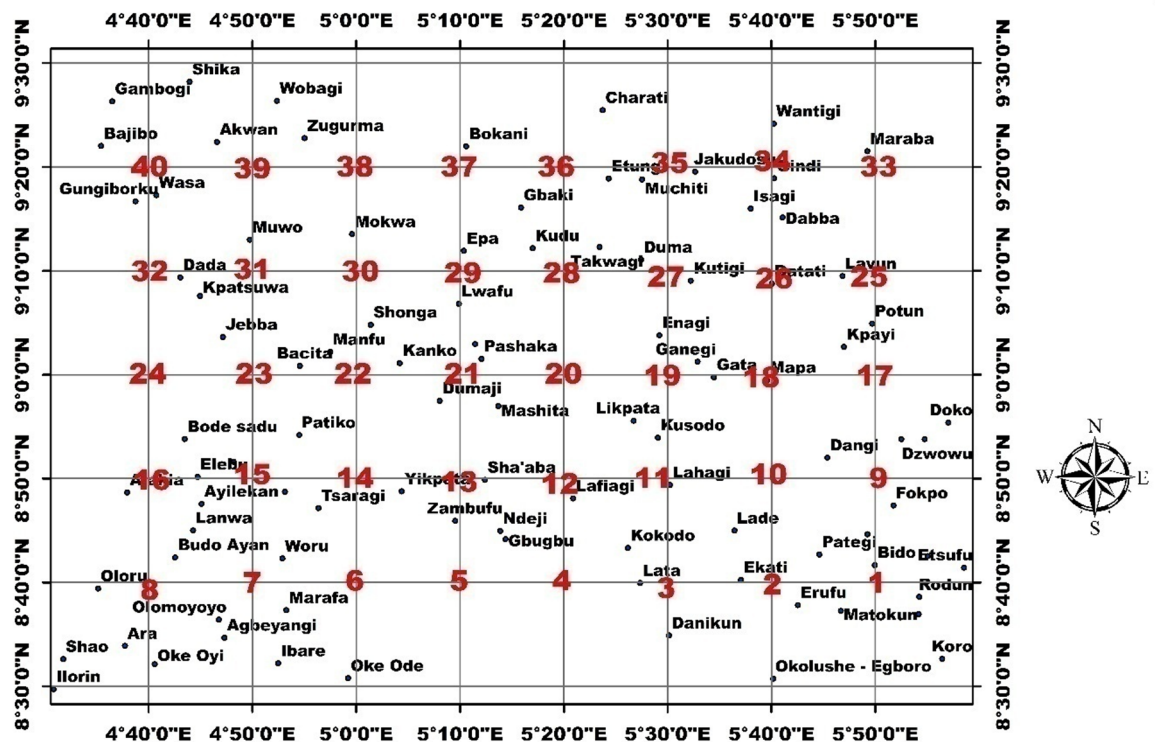


**Fig. 3.** Division of the study area into 40 overlapping spectral blocks for detailed analysis.

| Parameter               | Mean  | Std. Dev. | Min.  | Max.  | Median | CV (%) | Skewness | Kurtosis |
|-------------------------|-------|-----------|-------|-------|--------|--------|----------|----------|
| CPD (km)                | 37.79 | 5.84      | 25.56 | 46.11 | 38.64  | 15.45  | -0.423   | -0.287   |
| GTG (°C/km)             | 15.73 | 2.41      | 12.58 | 22.69 | 15.17  | 15.32  | 0.845    | 0.521    |
| HF (mW/m <sup>2</sup> ) | 39.33 | 6.12      | 31.45 | 56.73 | 37.93  | 15.56  | 0.891    | 0.498    |
| Z <sub>t</sub> (km)     | 5.36  | 1.87      | 2.22  | 9.23  | 5.37   | 34.89  | 0.127    | -0.456   |
| Z <sub>0</sub> (km)     | 21.57 | 3.12      | 15.26 | 27.34 | 21.64  | 14.46  | -0.089   | -0.512   |

**Table 1.** Descriptive data of geothermal parameters in the study area ( $n=40$ ).

and the upper range for quartz-rich granitoids<sup>30</sup>. Since  $GTG = \theta_c / Z_b$  is conductivity-independent, only  $HF = \sigma \times GTG$  is affected. Applying the study's mean GTG of  $16 \pm 2$  °C/km yields lower-bound HF of  $\sim 24$  mW/m<sup>2</sup>, baseline HF of  $\sim 40$  mW/m<sup>2</sup>, and upper-bound HF of  $\sim 56$  mW/m<sup>2</sup>, representing an uncertainty envelope of approximately  $\pm 40\%$ . Given that the study area occupies a TGE at the basement-sedimentary boundary, both end-member scenarios are geologically plausible: sediment-dominated zones are likely to return heat flow values closer to  $\sim 24$  mW/m<sup>2</sup>, while basement-proximal zones may approach  $\sim 56$  mW/m<sup>2</sup>. This duality does not affect the spatial ranking of the 12 identified high-potential zones, which are based on conductivity-independent CPD and GTG parameters. The values obtained from the geothermal parameters were utilised to systematically identify and delineate potential areas for geothermal energy resources throughout the study area.

### Statistical analysis on the geothermal parameters' relationships

Statistical analysis involving descriptive statistics, correlation analysis, multiple regression, principal component analysis (PCA), spatial analysis, and uncertainty assessment were carried out on geothermal parameters —  $Z_0$  (centroid depth),  $Z_t$  (depth to top of magnetic sources), CPD, GTG, HF—from the 40 spectral blocks. All statistical computations and risk analyses were performed using Python.

Prior to correlation and regression analyses, the distribution of each derived geothermal parameter was assessed for normality using the Shapiro-Wilk test ( $n=40$ ). It is important to emphasise that this normality assessment serves a strictly statistical purpose: it determines whether the assumptions underlying parametric inferential methods—specifically Pearson product-moment correlation, ordinary least squares multiple regression, and parametric PCA—are sufficiently met to justify their application. A non-significant Shapiro-

Wilk result ( $p > 0.05$ ) indicates that the data do not significantly depart from a Gaussian distribution, thereby supporting the use of these parametric methods. Critically, this statistical finding carries no physical interpretation: normality of a derived geothermal parameter does not imply that the underlying geological or thermal process is normally distributed, nor does it constitute evidence that the CPD, GTG, or HF values are physically accurate or geologically reasonable. The physical credibility of the estimates rests instead on the geophysical method, the assumed model parameters, and comparison with regional and global analogues.

Regression analysis was performed to establish relationships between geothermal parameters. A correlation matrix was developed to assess the strength of associations. PCA—a dimensionality reduction technique that transforms a set of correlated variables into uncorrelated components—was applied to identify underlying statistical structure in the dataset. The later components account for most of the variance, facilitating data analysis and visualisation.

## Results and discussion

### Interpretation of the residual magnetic structures

The Reduced-to-Equator Residual Magnetic Intensity (RTE RMI) map (Fig. 2) reveals magnetic signatures varying from  $-100$  to  $70$  nT, subdivided into low magnetic signatures (LMSs:  $-100$  to  $-33.84$  nT), intermediate magnetic signatures (IMSS:  $-33.84$  to  $19.58$  nT), and high magnetic signatures (HMSs:  $> 19.58$  nT). HMS clusters are observed in the southern, southeastern, northwestern, and parts of the western and northeastern regions. IMSSs are more pronounced in the central and northern regions. LMSs are most evident in the eastern and southwestern regions.

LMSs indicate deeply seated magnetic bodies or low-magnetic-mineral lithologies—including sandstones, sands, granites, and sedimentary rocks<sup>25</sup>—consistent with the thick sedimentary sequences of the Bida Basin in the eastern and southwestern regions. IMSSs reflect moderate magnetic constituents typical of metamorphic rocks<sup>31</sup>, or basalt and andesite in the northern NC region<sup>32</sup>. HMSs are attributed to near-surface, magnetically rich rocks—hematite ( $\text{Fe}_2\text{O}_3$ ), ilmenite ( $\text{FeTiO}_3$ ), and magnetite ( $\text{Fe}_3\text{O}_4$ )—present in the igneous and metamorphic rocks of the Precambrian Basement Complex (Fig. 1b)<sup>33</sup>. The spatial distribution of these magnetic signatures provides crucial insights into the subsurface geology, indicating variations in rock types, structural features, basement depth, and heat distribution relevant to geothermal reservoir identification.

### Estimation of the curie-point depths, geothermal gradients, and heat flow

Azimuthally averaged, wavenumber-scaled power spectra were derived for each of the 40 overlapping data blocks (Fig. 3) to estimate the depth to the bottom of the magnetic source (DBMS), serving as a proxy for CPD. Representative spectra for blocks 7 and 28 are presented in Fig. 4a and b. The high-wavenumber portion is used to calculate  $Z_t$ , while the low-wavenumber portion yields  $Z_o$ . The computed descriptive statistics of geothermal parameters ( $Z_t$ ,  $Z_o$ ,  $Z_b$  or CPD, GTG, and HF) from 40 spectral blocks are presented in Table 1. The Shapiro-Wilk test yielded  $W = 0.967$  ( $p = 0.285$ ), indicating no significant departure from normality—confirming the suitability of parametric methods for this dataset, though not constituting physical validation of CPD estimates themselves. The coefficient of variation ( $CV = 15.45\%$ ) indicates moderate spatial heterogeneity. GTG displayed positive skewness (0.845), indicating a concentration of lower values with fewer high-gradient zones. The mean gradient of  $15.73$  °C/km, while below the global average of  $25$  °C/km, demonstrates significant local variations supporting targeted geothermal development<sup>25,33</sup>.

As shown in Fig. 5, CPD values ranged from  $25.56$  to  $46.11$  km (mean:  $37.79$  km), with shallowest values clustering along the southwestern and south-central portions of the study area, coincident with the basement–sediment contact of the Bida Basin and NE–SW-trending fault corridors (e.g., Dangi, Patigi). Deeper CPDs in the northeastern and northwestern portions reflect cooler, thermally stable Precambrian basement-dominated crust (e.g., Borgu, Muwo). This spatial pattern is consistent with the known structural architecture of the Bida Basin, with CPD shallowing toward basin margins and fault-controlled basement highs, and deepening toward the basin depocentre where sedimentary insulation increases.

As revealed in Fig. 6, GTG ranged from  $12.58$  to  $22.69$  °C/km (mean:  $15.73$  °C/km), with elevated gradients exceeding  $17$  °C/km concentrated in the southwestern and south-central zones where CPDs are shallowest and basement–sediment contacts are most structurally complex. This spatial correspondence suggests the geothermal gradient is primarily controlled by structural lithospheric thinning and basement-penetrating fault systems, with gradients declining progressively northward into the basin interior.

As shown in Fig. 7, HF, estimated using  $\sigma = 2.5 \text{ W m}^{-1}\text{°C}^{-1}$ , ranged from  $31.45$  to  $56.73$  mW/m<sup>2</sup> (mean:  $39.33$  mW/m<sup>2</sup>), replicating the CPD and GTG spatial patterns. Peak HF values exceeding  $50$  mW/m<sup>2</sup> are concentrated in the same SW–south-central structural corridor, while lowest values occur in the NE basin interior. This three-parameter spatial coherence reinforces the interpretation that heat anomalies are geologically controlled by basement fault architecture rather than surficial factors. The spatial distribution of fluid flow vectors reveals a hydrothermal system driven by thermal buoyancy and regional geothermal gradients. Fluid migration is predominantly divergent, originating from high-heat-flow hotspots and discharging toward lower-intensity thermal sinks. In the central and north-central sectors, a strong north-to-northeasterly flow orientation suggests deep-seated upwelling toward the northern basin margins. The western sector around the Jebba–Kpatsuwa axis shows convergent flow toward localised thermal lows ( $\sim 36$  mW/m<sup>2</sup>), indicating potential structural or lithological traps for descending fluids. The high flux density in the central-eastern corridor, proximal to thermal anomalies exceeding  $50$  mW/m<sup>2</sup>, identifies these hotspots as the primary engines of hydrothermal circulation, facilitated by basement-rooted fracture networks. Given the TGE setting, this pattern reflects the combined influence of sedimentary insulation and basement structural conduits, underscoring a thermally regulated hydrodynamic regime across the study area.

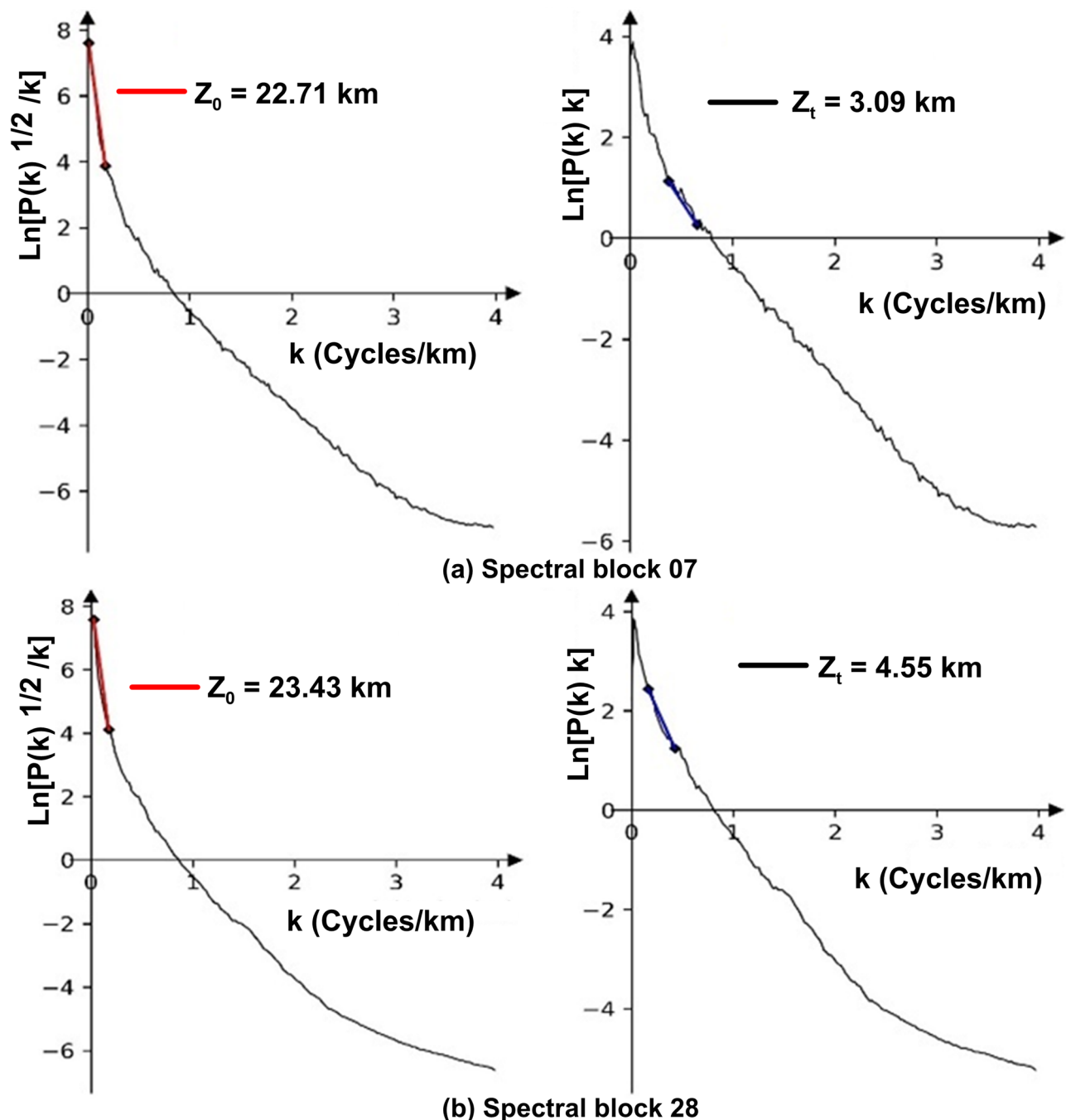


**Fig. 4.** Azimuthally averaged, wave-number-scaled power spectra for representative blocks: (a) Block 07 and (b) Block 28, used for estimating magnetic source depths.

The mean heat flow of  $\sim 39 \text{ mW/m}^2$  is most consistent with sediment-dominated zones, though basement-proximal zones may approach  $\sim 56 \text{ mW/m}^2$ . Both values fall below the  $\sim 80 \text{ mW/m}^2$  threshold for conventional binary-cycle electricity generation, making direct-use applications — ground source heat pump (GSHP) systems, agricultural drying, aquaculture heating, and low-temperature industrial process heat — the primary development pathway. Localised peaks above  $50 \text{ mW/m}^2$  in the 12 identified hotspot zones may approach the minimum threshold for small-scale binary organic Rankine cycle (ORC) systems, pending borehole confirmation. These results are consistent with findings by Megwara et al.<sup>5</sup>, Nwankwo and Sunday<sup>6</sup>, Salaudeen et al.<sup>19</sup>, Usman et al.<sup>25</sup>, and Gaber et al.<sup>33</sup>.

#### Comparative analysis of geothermal studies in Nigeria using aeromagnetic data

The present study yields a higher mean CPD of  $37.79 \text{ km}$ , but lower mean GTG of  $15.73 \text{ }^\circ\text{C/km}$  and HF of  $39.33 \text{ mW/m}^2$  compared with existing literature, as revealed in Table 2. This likely reflects the thick sedimentary

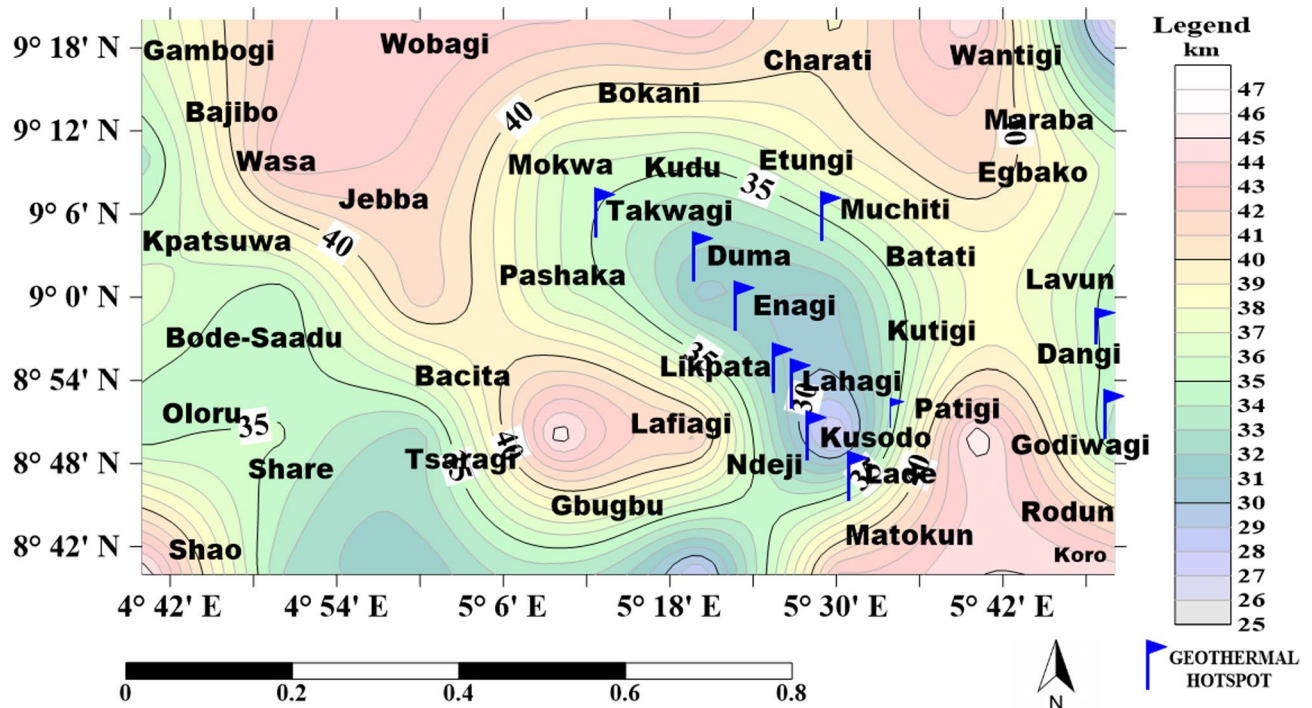


Fig. 5. Curie point depth (unit: km) map of the Egbako–Share axis, North-Central Nigeria. Contour interval is 1 km, Grid cell size is  $58 \times 100$  m, & UTM Zone is 32 N (WGS84).

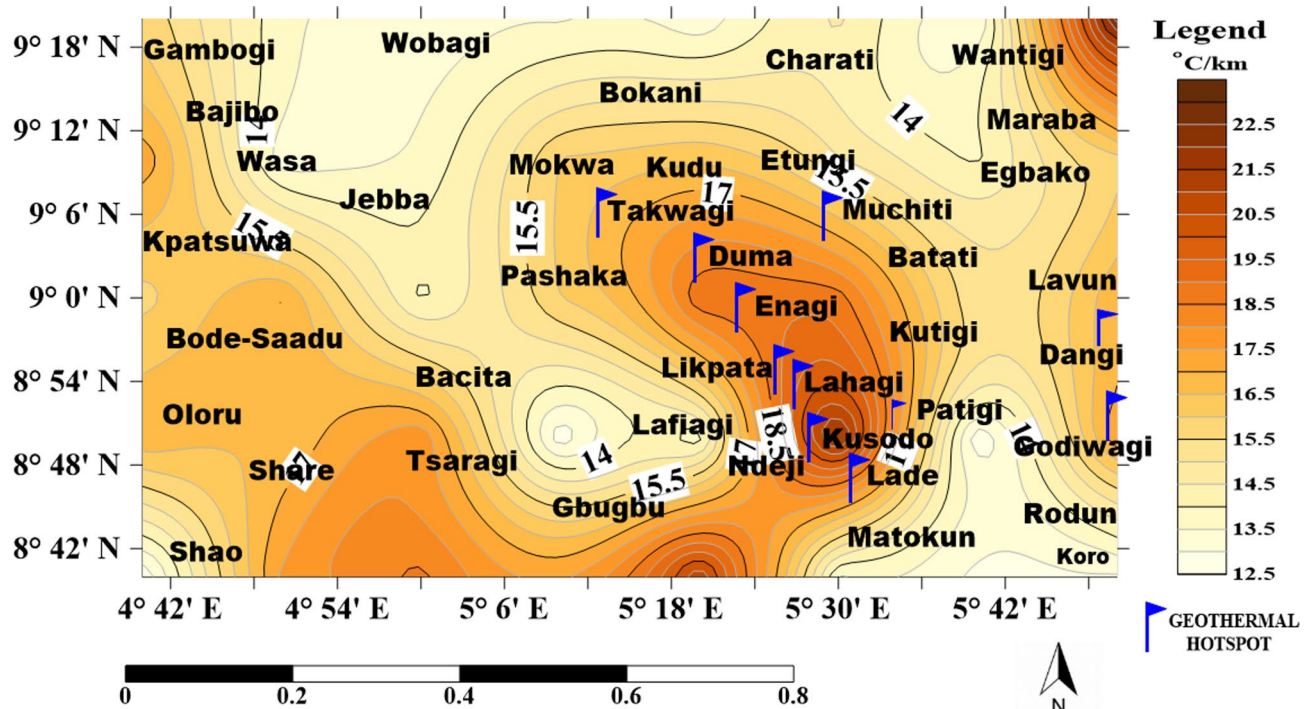


Fig. 6. Geothermal gradient (unit:  $^{\circ}\text{C}/\text{km}$ ) map of the Egbako–Share axis, North-Central Nigeria. Contour interval is  $0.5^{\circ}\text{C}/\text{km}$ , Grid cell size is  $58 \times 100$  m, & UTM Zone is 32 N (WGS84).

overburden in the southern Bida Basin, which limits upward heat transfer. Areas exhibiting moderate geothermal potential ( $\text{HF} \sim 60 \text{ mW}/\text{m}^2$ ; gradient  $20\text{--}30^{\circ}\text{C}/\text{km}$ ), such as the identified high-potential zones, are unsuitable for large-scale electricity generation—which typically requires  $> 80 \text{ mW}/\text{m}^2$ —but are highly viable for small-scale direct thermal applications. This implies that the identified “sustainable energy pathway” is

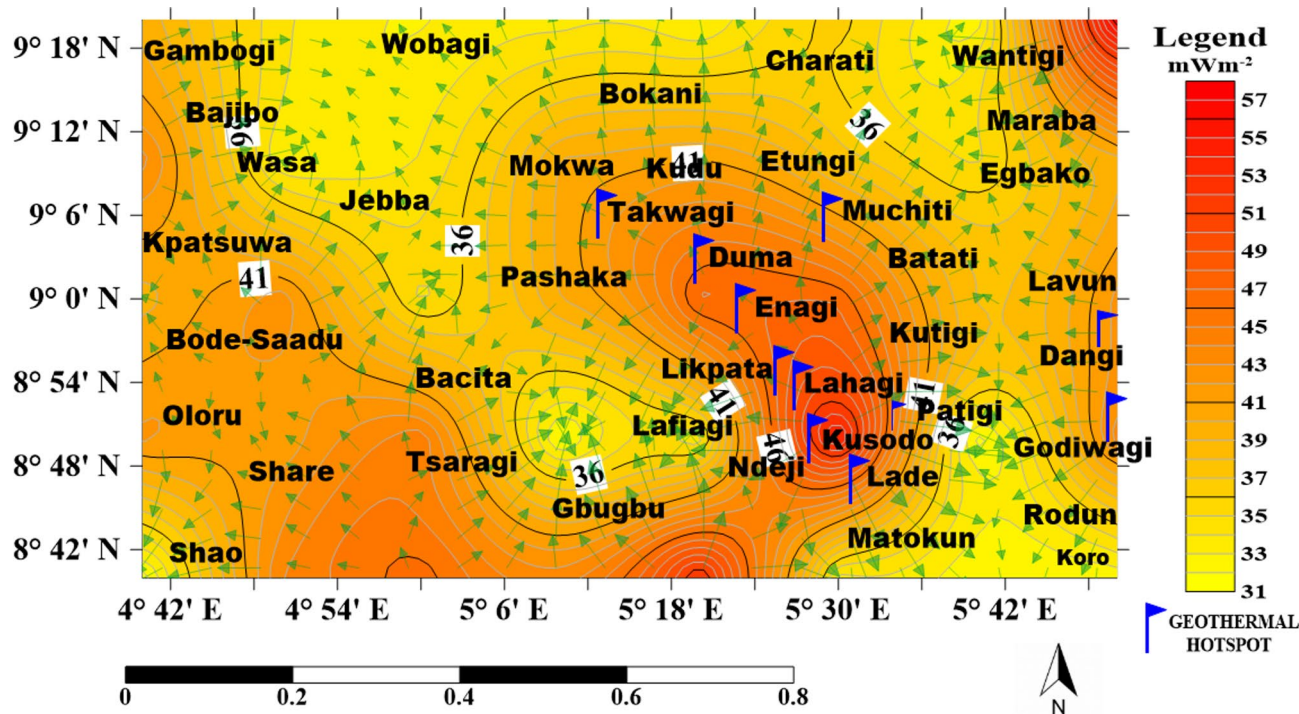


Fig. 7. Heat flow (unit:  $\text{mW/m}^2$ ) map of the Egbako–Share axis, North-Central Nigeria. Contour interval is  $1 \text{ mW/m}^2$ , Grid cell size is  $58 \times 100 \text{ m}$ , & UTM Zone is 32 N (WGS84).

| Study Area                      | CPD Range (km) | Avg. CPD (km) | GTG Range ( $^{\circ}\text{C}/\text{km}$ ) | Avg. GTG ( $^{\circ}\text{C}/\text{km}$ ) | HF Range ( $\text{mW/m}^2$ ) | Avg. HF ( $\text{mW/m}^2$ ) | Hotspots Identified                 | Location of the Study |
|---------------------------------|----------------|---------------|--------------------------------------------|-------------------------------------------|------------------------------|-----------------------------|-------------------------------------|-----------------------|
| This Study                      | 25.56–46.11    | 37.79         | 12.58–22.69                                | 15.73                                     | 31.45–56.73                  | 39.33                       | Dangi, Lade, Patigi, Kusodo         | Egbako–Share axis, NC |
| Mohammed et al. <sup>41</sup>   | 12.43–33.91    | 18.83         | 17.10–46.66                                | 30.75                                     | 42.75–116.65                 | 75.91                       | Lau, Guyok, Dong                    | Benue, NC             |
| Udochukwu et al. <sup>42</sup>  | 10.32–24.48    | 13.39         | 23.70–56.21                                | 46.2                                      | 59.24–136.18                 | 112.36                      | Northeastern and southwestern areas | Chad Basin, NE        |
| Nwankwo and Sunday <sup>6</sup> | 15.57–29.62    | 21.65         | 19.58–37.25                                | 27.25                                     | 48.41–93.12                  | 68.8                        | Central and northwestern regions    | Bida-Basin, NC        |
| Salaudeen et al. <sup>19</sup>  | 34.09–55.19    | 41.87         | 10.51–17.01                                | 14.13                                     | 26.27–42.53                  | 35.32                       | Kusaji, Rogun, Sankwafuji           | Bida Basin, NC        |
| Tsepav and Mallam <sup>43</sup> | 2.59–8.23      | 5.17          | 70.45–224.15                               | 120.66                                    | 176.13–560.37                | 301.66                      | Kotonkarfi                          | Bida Basin, NC        |

Table 2. Comparative analysis of geothermal studies in Nigeria using aeromagnetic data.

highly specialised, focusing on decentralised direct-use applications including rural electrification, greenhouse heating, and industrial pre-heating. Comparative analysis with previous Nigerian geothermal studies reveals significant regional variations; the CPD in this study averages  $37.79 \text{ km}$  against a regional average of  $22.64 \text{ km}$ , while thermal parameters remain lower. However, direct numerical comparison across Nigerian basins must be interpreted with caution. The studies compiled in Table 2 span tectonically distinct settings: the Benue Trough is a Cretaceous rift with extensional tectonics and thin crust, fundamentally different from the intracratonic, conduction-dominated Bida Basin. Thus, these thermal results should not be read as indicating inferior potential, but rather a different, direct-use-appropriate resource type.

The significance of these results is further sharpened by comparison with international low-enthalpy success cases like Denmark’s Norwegian–Danish and North German Basins. These classic low-enthalpy settings feature Mesozoic sandstone reservoirs at depths of  $800\text{--}3,000 \text{ m}$  with temperatures of  $40\text{--}80 \text{ }^{\circ}\text{C}$ , broadly overlapping the theoretical potential of the Egbako–Share axis<sup>34</sup>. Denmark has successfully operated geothermal district heating plants since 1984, demonstrating commercial confidence in moderate-gradient sedimentary systems<sup>34,35</sup>. Three transferable lessons are directly applicable here: (i) pre-existing district heating infrastructure is the most critical determinant of viability—Nigeria’s absence of such networks constitutes a primary gap; (ii) systematic reservoir characterization of the Batati, Agbaja, and Lokoja sequences is a prerequisite for reducing exploration risk; and (iii) state-backed risk-sharing mechanisms are necessary to mobilize commercial finance. Furthermore, recent GIS-based assessments in Sub-Saharan intracratonic basins demonstrate that shallow GSHP systems at  $50\text{--}300 \text{ m}$  can offset approximately  $2,900 \text{ t CO}_2$  equivalent per installation annually<sup>3</sup>. While the present study’s peak HF of

56.73 mW/m<sup>2</sup> falls just below the 65–85 mW/m<sup>2</sup> range observed in East African conduction-dominated plays, it confirms that successful development will depend critically on identifying structurally controlled thermal anomalies<sup>36–40</sup>.

### Real-world analogues: temperature–depth profiles from comparable low-enthalpy transitional settings

To contextualise the derived geothermal parameters within a global framework, three documented analogues from comparable low-enthalpy TGEs are examined. These were selected because their geological controls—intracratonic subsidence, conduction-dominated heat transfer, basement–sediment interfaces, and fault-assisted fluid pathways—closely mirror the Egbako–Share axis TGE.

- i. Pannonian Basin, Hungary (intracratonic rift with Neogene basin fill): The Pannonian Basin is one of the most extensively documented low-to-medium-enthalpy geothermal provinces globally. Formed by Miocene crustal extension, it features HF averaging 90–100 mW/m<sup>2</sup> and geothermal gradients of 45–60 °C/km in the upper 1,500 m<sup>44</sup>, with over 1,600 thermal wells documenting temperatures of 70–140 °C at 1,000–2,000 m depth. By contrast, the Egbako–Share axis records a mean GTG of 15.73 °C/km and HF of 39.33 mW/m<sup>2</sup>—approximately one-third and one-half of Pannonian values respectively—confirming its placement within the moderate-to-low enthalpy tier. Nevertheless, the basin demonstrates that gradients of 13–20 °C/km in thermally subdued sub-basins still support viable GSHP operations, a technology directly transferable to this study's high-potential zones.
- ii. Vienna Basin, Austria (transform pull-apart basin with Miocene sedimentary fill): The Vienna Basin exhibits a geothermal gradient of approximately 22 °C/km and a basement–sediment architecture closely analogous to the present study<sup>45</sup>. A 2021 production test at the Miocene Rothneusiedl Formation (2,640–2,700 m depth) yielded a wellhead temperature of 86 °C, confirming economically viable reservoir conditions for district heating. The GeoTief Wien project estimates the basin holds 40–60% of Austria's total usable hydrothermal capacity, with the Aspern plant (20 MWth, ~20,000 households, CO<sub>2</sub> savings up to 54,000 t/year) as its first commercial realisation. Critically, the Vienna Basin demonstrates that a gradient as low as 22 °C/km—comparable to the upper range of this study's 12.58–22.69 °C/km distribution—is sufficient to sustain commercial district heating at depths accessible with modern directional drilling, validating the potential of the 12 identified high-potential zones.
- iii. Büyük Menderes Graben, Western Anatolia, Turkey (Neogene extensional graben with metamorphic basement): While the graben's central fields operate as high-enthalpy systems (e.g., Kizildere, 242 °C), its marginal low-to-medium enthalpy zones are most relevant in this study. Fields along the BMG margin—Pamukkale (36 °C), Karahayit (59 °C), and Golemezli (101 °C)—produce hot water from reservoirs at 500–2,000 m depth, supporting direct-heat and balneological applications<sup>46</sup>. More importantly, the BMG illustrates that fault-assisted fluid migration steepens local temperature–depth gradients near graben-bounding faults by a factor of two to three above the background conductive value—a mechanism consistent with heat-flow anomalies at blocks 1, 27, and 36, which may reflect structurally controlled upwelling along basement–sedimentary margin contacts.

Collectively, these analogues confirm that commercially exploitable geothermal conditions occur across gradients of 22–60 °C/km and HF of 60–130 mW/m<sup>2</sup>. The Egbako–Share axis, with a maximum gradient of 22.69 °C/km and HF peaks of 56.73 mW/m<sup>2</sup>, occupies the lower end of this spectrum but remains within the established viability window for direct-use applications. Shallow boreholes (300–500 m) at Dangi, Lade, and Patigi should confirm subsurface temperatures 15–25 °C above ambient, with possibly 60–80 °C at 2,000–3,500 m where structural fluid upwelling exists.

### Statistical analyses of geothermal parameters

The histogram of CPD (Fig. 8) shows a wide distribution concentrated between 30 and 45 km, suggesting most of the study area lies within crustal depths suitable for geothermal exploration<sup>25</sup>. The box plot (Fig. 9) confirms a median GTG of ~15 °C/km, ranging from 12.58 to 22.69 °C/km—suitable for medium-temperature systems such as GSHP and district heating<sup>31</sup>. Regions combining low CPD with high GTG and HF are considered geothermal hotspots suitable for direct-use low-enthalpy development<sup>33</sup>.

The correlation matrix (Table 3) reveals strong negative relationships between CPD and derived thermal parameters. The CPD–GTG correlation ( $r = -0.892$ ,  $p < 0.001$ ) confirms the expected inverse relationship between magnetic source depth and geothermal gradient. The near-perfect GTG–HF correlation ( $r = 0.999$ ) reflects mathematical dependence rather than independent empirical confirmation: since HF is computed as  $HF = \sigma \times GTG$  using a single assumed thermal conductivity constant, the two variables are linearly dependent by construction. This validates internal computational consistency, not physical accuracy, and cannot be treated as independent corroboration. The strong CPD–HF correlation ( $r = -0.891$ ) is consistent with geothermal systems where deeper formations generally exhibit lower surface heat conduction, while the moderate CPD– $Z_0$  correlation ( $r = 0.712$ ) reflects systematic variations in magnetic source geometry across the study area. The CPD–GTG scatter plot (Fig. 10) visually reinforces this negative relationship, confirming that shallower regions experience more significant geothermal heating and are most suitable for district heating, hot water supply, and direct-use applications<sup>33,47–50</sup>.

Multiple regression analysis was performed to develop predictive models for HF estimation. In Eq. 1, it was revealed that CPD and  $Z_0$  are independent variables.

$$HF = 147.83 - 2.51 (CPD) + 0.34(Z_0) \quad (1)$$

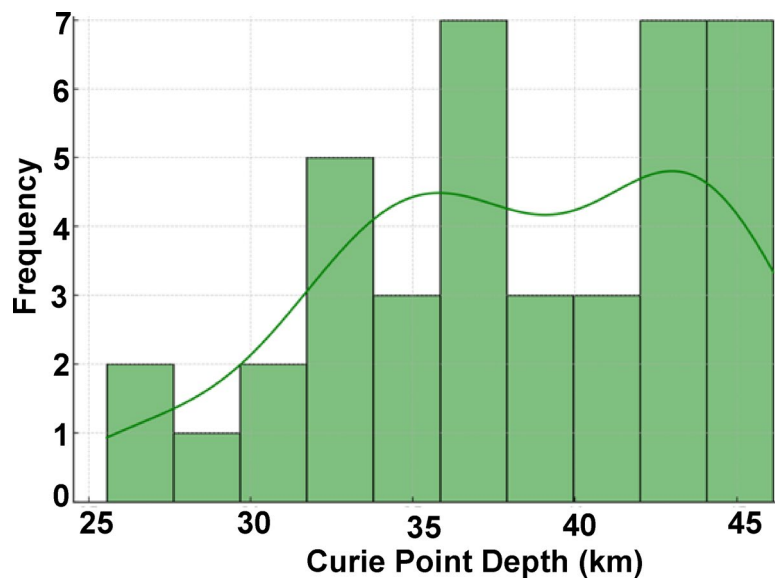


Fig. 8. Histogram for CPD.

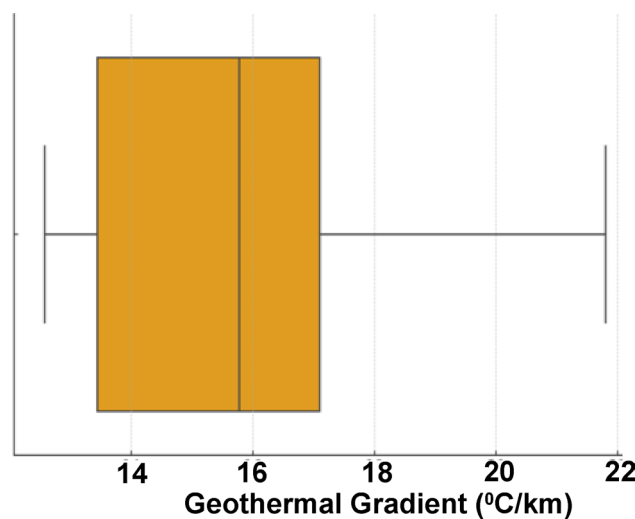


Fig. 9. Boxplot for GTG.

|       | CPD       | GTG       | HF        | $Z_t$  | $Z_0$     |
|-------|-----------|-----------|-----------|--------|-----------|
| CPD   | 1.000     | -0.892*** | -0.891*** | -0.234 | 0.712***  |
| GTG   | -0.892*** | 1.000     | 0.999***  | 0.089  | -0.634*** |
| HF    | -0.891*** | 0.999***  | 1.000     | 0.091  | -0.631*** |
| $Z_t$ | -0.234    | 0.089     | 0.091     | 1.000  | -0.156    |
| $Z_0$ | 0.712***  | -0.634*** | -0.631*** | -0.156 | 1.000     |

**Table 3.** Correlation matrix of geothermal parameters. \*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ .

Model statistics:  $R^2 = 0.795$ , adjusted  $R^2 = 0.784$ , F-statistic = 72.46 ( $p < 0.001$ ), RMSE = 2.84 mW/m<sup>2</sup>. CPD is the dominant predictor ( $\beta = -0.891$ ,  $p < 0.001$ ), explaining 79.5% of heat flow variance. Importantly, this is a descriptive model characterising spatial covariation within the study area—not a predictive model of drilling-scale performance. It must not be used to forecast borehole temperatures, reservoir productivity, or commercial viability, as it excludes direct subsurface measurements, lithological heterogeneity, hydraulic properties, and

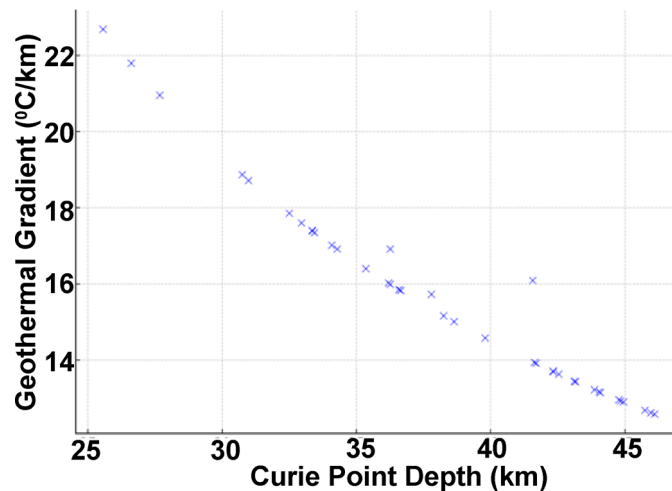


**Fig. 10.** Visual relationship between CPD and GTG.

depth-dependent CPD uncertainties. Residual analysis confirmed normally distributed residuals and constant variance.

Principal component analysis identified underlying statistical structure, with the first two PCs explaining 89.7% of total variance. PC1 (76.4%) showed high loadings on GTG (0.951), HF (0.950), and CPD (−0.934), capturing the dominant covariance structure between shallow CPD and elevated GTG and HF. Given the functional dependence among these variables, the high variance explained by PC1 does not independently evidence a distinct geological process; interpretations involving crustal thinning, granitic intrusions, or fault-facilitated heat advection remain hypotheses requiring confirmation through independent geophysical and borehole data. PC2 (13.3%), with high loadings from Zt (0.823) and Z<sub>0</sub> (0.687), represents magnetic source geometry and structural controls, reflecting variations in sedimentary thickness or buried magnetic bodies. Cluster analysis identified three geothermal zones: (1) high-potential ( $n=8$ ;  $CPD < 35$  km;  $GTG > 17$  °C/km); (2) moderate-potential ( $n=24$ ;  $35–42$  km;  $GTG$  13–17 °C/km); and (3) low-potential ( $n=8$ ;  $CPD > 42$  km;  $GTG < 13$  °C/km).

Spatial autocorrelation (Moran's  $I=0.387$ ,  $p=0.002$ ) confirms non-random clustering controlled by fault systems, basement depth variations, and lithological contacts. Getis-Ord  $G_i^*$  analysis identified 12 statistically significant high-potential clusters. The thresholds applied ( $GTG > 17$  °C/km;  $HF > 40$  mW/m<sup>2</sup>) represent the upper quartile of the study area's own distributions—not globally established commercial viability minima—and are consistent with analogous reconnaissance-level CPD studies in intracratonic settings<sup>6,25</sup>. The 12 zones in descending order are: Block 1 (22.69 °C/km; 56.73 mW/m<sup>2</sup>), Block 27 (21.80; 54.51), Block 36 (20.96; 52.40), Block 20 (18.87; 47.17), Block 19 (18.72; 46.80), Block 38 (18.60; 46.50), Block 30 (17.85; 44.63), Block 39 (17.60; 44.01), Block 25 (17.40; 43.49), Block 37 (17.39; 43.48), Block 16 (17.35; 43.37), and Block 23 (17.02; 42.56). Bootstrap resampling ( $n=1,000$ ; 95% CI) confirmed:  $CPD = 37.79 \pm 0.92$  km;  $GTG = 15.73 \pm 0.38$  °C/km;  $HF = 39.33 \pm 0.97$  mW/m<sup>2</sup>. Monte Carlo simulation confirmed robustness of the high-potential zones, with 87% probability of exceeding viability thresholds.

### SDG alignment and economic assessment

The identified geothermal resources present significant sustainable development opportunities. Full development of all 12 hotspot zones is modelled to yield an aggregate installed capacity of 15–25 MWth and annual generation of 120–200 GWh/year—indicative order-of-magnitude estimates scaled from comparable intracratonic case studies, not engineering feasibility outputs. The projected LCOE of 0.08–0.12 USD/kWh reflects published benchmarks for low-enthalpy GSHP systems<sup>51</sup>. A scenario-based CO<sub>2</sub> reduction of 85,000–140,000 t/year supports SDG 13 (Climate Action), while lifecycle carbon intensity of 18–45 g CO<sub>2</sub>/kWh aligns with Nigeria's NDC targets. Additional co-benefits include local employment (SDG 8), technology transfer (SDG 9), and community energy access (SDG 11).

Table 4 presents CAPEX, OPEX, and economic performance indicators across three project categories: low-enthalpy direct-use systems; high-enthalpy electricity generation; and a subsidy-adjusted transitional scenario. Three findings are financially significant. First, a 5 MW low-enthalpy unit (USD 5–15 million CAPEX) costs three to four times less than a comparable high-enthalpy project. Second, stacking REA grants (30%), World Bank DARES subsidies (40%), and AfDB SEFA concessional loans (2–5% p.a.) improves IRR from 6 to 12% to 10–18% and compresses SPP from 8 to 15 to 5–10 years. Third, the subsidy-adjusted LCOE of USD 0.05–0.09/kWh substantially undercuts rural diesel mini-grid costs (USD 0.25–0.35/kWh). Article 6 carbon credits could generate supplementary revenue of USD 1.3–6.3 million per year across all 12 installations.

### Environmental risks and mitigation strategies

Although low-enthalpy geothermal systems are among the least environmentally disruptive energy extraction methods, development within TGEs introduces site-specific risks requiring systematic assessment. These arise

| Metric                                                               | Low-Enthalpy Direct-Use (This Study)                                                                                                                       | High-Enthalpy Electricity Generation (Global Benchmark)                                                                                 | Low-Enthalpy with Transitional Zone Subsidies (Nigeria-Adjusted)                                                                         |
|----------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Reservoir type                                                       | Sedimentary / basement-contact aquifer; $T < 100\text{ }^{\circ}\text{C}$ ; GTG 12.58–22.69 $^{\circ}\text{C}/\text{km}$ ; HF 31–57 $\text{mW}/\text{m}^2$ | Volcanic / magmatic; $T > 150\text{ }^{\circ}\text{C}$ ; GTG $> 80\text{ }^{\circ}\text{C}/\text{km}$ ; HF $> 100\text{ mW}/\text{m}^2$ | Same as low-enthalpy; concessional financing applied                                                                                     |
| Target applications                                                  | District heating, aquaculture, crop drying, ground-source heat pumps (GSHP), rural electrification (ORC binary)                                            | Grid-scale electricity generation (flash steam, dry steam)                                                                              | Same as low-enthalpy; priority for rural off-grid communities near hotspots                                                              |
| Typical well depth                                                   | 500–2,500 m                                                                                                                                                | 1,500–4,000 m                                                                                                                           | 500–2,500 m                                                                                                                              |
| CAPEX – Exploration & drilling (USD million per well)                | 0.5–2.0 M USD/well (shallow; sedimentary aquifer)                                                                                                          | 3.0–8.0 M USD/well (deep; hard rock)                                                                                                    | 0.4–1.4 M USD/well (after 20–30% grant/concessional offset via REA/SEFA)                                                                 |
| CAPEX – Surface plant & infrastructure (USD million per MWe or MWth) | 0.3–1.5 M USD/MWth (heat exchanger, pipework, GSHP units, ORC module if binary)                                                                            | 2.0–5.0 M USD/MWe (flash turbine, separator, cooling tower)                                                                             | 0.2–1.1 M USD/MWth (DARES grant covers up to 40% of surface plant cost for off-grid rural projects)                                      |
| Total project CAPEX (USD million, indicative 5 MW unit)              | 5–15 M USD                                                                                                                                                 | 25–60 M USD                                                                                                                             | 3–10 M USD (after subsidy stack)                                                                                                         |
| OPEX (USD/MWh or USD/MWth/year)                                      | 10–40 USD/MWh (pumping, maintenance, water management; no fuel cost)                                                                                       | 15–50 USD/MWh (fluid re-injection, $\text{H}_2\text{S}$ abatement, brine management)                                                    | 8–30 USD/MWh (local labour cost advantage; no $\text{H}_2\text{S}$ treatment required)                                                   |
| LCOE (USD/kWh)                                                       | 0.08–0.12 USD/kWh (consistent with study estimate)                                                                                                         | 0.04–0.10 USD/kWh (lower at scale; high resource quality offsets deep drilling CAPEX)                                                   | 0.05–0.09 USD/kWh (subsidy reduces effective CAPEX; brings LCOE below diesel mini-grid at ~0.25–0.35 USD/kWh in rural Nigeria)           |
| Simple payback period (SPP)                                          | 8–15 years                                                                                                                                                 | 5–10 years (larger revenue base at scale)                                                                                               | 5–10 years (subsidy closes financing gap; shortened vs. unsubsidised baseline)                                                           |
| IRR (%)                                                              | 6–12%                                                                                                                                                      | 12–20%                                                                                                                                  | 10–18% (subsidy raises IRR to commercially bankable threshold of ~10%)                                                                   |
| $\text{CO}_2$ abatement cost (USD/tonne $\text{CO}_2$ avoided)       | 20–60 USD/tonne (lifecycle intensity: 18–45 g $\text{CO}_2/\text{kWh}$ )                                                                                   | 10–30 USD/tonne (at scale; larger absolute $\text{CO}_2$ displacement per plant)                                                        | 15–45 USD/tonne (eligible for Article 6 carbon credit revenue under Nigeria's NDC framework, partially offsetting OPEX)                  |
| Project lifetime                                                     | 25–30 years                                                                                                                                                | 30–50 years                                                                                                                             | 25–30 years                                                                                                                              |
| Key financing instruments available                                  | Commercial bank debt; development finance (AfDB, IFC); climate bonds                                                                                       | Project finance; export credit agencies; IPP structures                                                                                 | REA grants (up to 30% CAPEX); World Bank DARES (40% surface plant); AfDB SEFA; Article 6 carbon credits; concessional loans at 2–5% p.a. |

**Table 4.** Comparative CAPEX/OPEX and economic performance metrics for low-enthalpy, high-enthalpy, and subsidy-adjusted transitional geothermal projects. Sources: IRENA<sup>51</sup>, Renewable Power Generation Costs; IGA<sup>7</sup>, Best Practices for Geothermal Resource Classification; Gehringer & Loksha<sup>52</sup>, Geothermal Handbook: Planning and Financing Power Generation, ESMAP Technical Report 002/12, World Bank; REA Nigeria<sup>53</sup>, Energising Rural Transformation Programme Guidelines; World Bank<sup>54</sup> DARES Project Appraisal Document. All values are indicative ranges; final project costs will require site-specific feasibility studies incorporating actual well productivity, fluid chemistry, surface infrastructure requirements, and prevailing foreign exchange rates.

from the dual-permeability architecture of TGEs, where thermally conductive crystalline basement rocks are juxtaposed against permeable sedimentary sequences, creating conditions for fluid pathway interconnection, fault reactivation, and aquifer cross-contamination. Three primary risk categories are addressed below, drawing on post-2020 studies and EU Renewable Energy Directive III (Directive EU/2023/2413).

#### Induced seismicity

Induced seismicity occurs when pore pressure or thermoelastic stress changes alter effective normal stress on pre-existing faults, triggering slip events<sup>55,56</sup>. Three factors present moderate seismic risk along the Egbako–Share axis: (i) the NE–SW and NW–SE fault network (Fig. 1b) retains residual Pan-African tectonic stresses<sup>11,15,55</sup>; (ii) spatial autocorrelation results (Moran's  $I = 0.387$ ) confirm that geothermal anomaly clusters are structurally controlled, meaning permeable fault zones elevating heat flow also represent preferential pressure transmission pathways during fluid injection; and (iii) CPDs of approximately 25–28 km at blocks 1, 27, and 36 place the Curie isotherm close to the brittle–ductile transition.

The recommended mitigation standard is the Traffic Light Protocol (TLP), with thresholds of  $M_1 = 0.5$  and  $M_2 = 2.0$  for low-background-seismicity intracratonic settings such as the Bida Basin margin<sup>57,58</sup>. Pre-injection three-dimensional geomechanical modelling should identify critically stressed fault segments and define site-specific TLP thresholds prior to any fluid injection operations<sup>59,60</sup>.

#### Groundwater contamination

Bida Basin sedimentary sequences host shallow aquifers supplying drinking and irrigation water throughout the study area<sup>15</sup>. Primary contamination vectors include: (i) upward migration of deep geothermal brines carrying dissolved chlorides, boron, arsenic, lithium, and fluoride along fault pathways or via well casing failures<sup>61,62</sup>; (ii) thermal plume propagation from open-loop GSHP systems; and (iii) introduction of drilling fluids. Mitigation requires multi-string well casing design isolating geothermal production from potable aquifers, mandatory total fluid reinjection into the producing horizon, and a pre-development groundwater baseline survey. No in-situ

groundwater surveys were conducted in this study; detailed monitoring design should be developed within a dedicated pre-feasibility environmental baseline study.

#### *Land subsidence*

Subsidence risk is substantially lower in low-enthalpy intracratonic settings than in high-enthalpy fields, but is not negligible given that Bida Basin Cretaceous sequences include shale and sandstone units with porosities of 15–25%. Mitigation requires strict fluid balance monitoring—ensuring reinjected mass equals or exceeds production—coupled with annual levelling surveys or satellite-based InSAR monitoring to detect subsidence precursors before exceeding the 5 mm/year infrastructure damage threshold<sup>61</sup>.

#### *Regulatory framework*

Nigeria currently lacks a dedicated geothermal regulatory instrument. EU RED III (Directive EU/2023/2413, November 2023) represents current global best practice, mandating environmental impact assessments (EIAs) as a prerequisite for geothermal permits, establishing renewables acceleration areas requiring pre-screening for environmental sensitivity, and explicitly including geothermal heating within its 1.1% per annum renewable heating increment obligation. It is strongly recommended that Nigeria's Federal Ministry of Environment, working with the Rural Electrification Agency and NGSA, develop a dedicated Low-Enthalpy Geothermal Development Regulation modelled on RED III requirements and adapted to the Bida Basin–Basement Complex transitional zone.

## Conclusion and recommendation

### Conclusion

This study provides a reconnaissance-level geothermal screening of the Egbako–Share axis of North-Central Nigeria, a transitional zone between Precambrian crystalline basement and Cretaceous Bida Basin sedimentary rocks. Using high-resolution aeromagnetic data and multivariate statistical analysis; CPD, GTG, and HF were estimated across 40 spectral blocks. The findings constitute a spatially screened framework to guide targeted field investigations, not a basis for investment or engineering decisions.

The analysis identified low-enthalpy geothermal potential characterised by CPDs of 25.56–46.11 km (mean 37.79 km), GTGs of 12.58–22.69 °C/km (mean 15.73 °C/km, ) and HFs of 31.45–56.73 mW/m<sup>2</sup> (mean 39.33 mW/m<sup>2</sup>). These values preclude conventional electricity generation but support direct-use low-enthalpy applications. Statistical correlations ( $r > 0.89$ ) partly reflect mathematical dependence between CPD-derived parameters rather than independent physical validation, and the regression model ( $R^2 = 0.795$ ) describes spatial covariance within this dataset only. Twelve blocks exceeding relative thresholds of GTG  $> 17$  °C/km and HF  $> 40$  mW/m<sup>2</sup> were identified as priority zones for field investigation.

Under a conceptual full-development scenario, modelled aggregate installed capacity of 15–25 MW could yield annual CO<sub>2</sub> reductions of 85,000–140,000 t/year—indicative figures contingent on confirmatory drilling and feasibility studies—offering directional support for SDG 7 and SDG 13, with indirect contributions to SDGs 8, 9, and 11 through employment, technology transfer, and decentralised energy access.

### Recommendations

Recommendations are structured in two tiers: **Tier A** (essential scientific next steps required to confirm or refute the aeromagnetic-derived screening results before any development decision) and **Tier B** (supporting and contextual actions preparatory to longer-term development).

#### *Tier A—Essential scientific next steps*

Shallow temperature gradient boreholes should be deployed at the 12 hotspot zones to ground-truth CPD-derived estimates and confirm thermal anomalies. Magnetotelluric surveys across these zones would map fluid pathways and reservoir geometry through deep resistivity imaging. Exploration boreholes should be prioritised at Dangi, Lade, and Godiwagi to obtain direct subsurface temperature, lithological, and fluid data essential for confirming reservoir viability and addressing the absence of borehole calibration data constraining current CPD-derived estimates. Concurrently, thermal water and soil gas geochemical surveys should characterise fluid–rock interaction, while ambient noise seismology and microseismic monitoring should establish the induced seismicity hazard profile of the fault network prior to any fluid injection operations.

#### *Tier B—Supporting and contextual actions*

Seismic and gravity data should be integrated into three-dimensional structural models, alongside hydraulic testing of target formations whose properties remain undocumented. Comprehensive EIAs addressing induced seismicity, land use, and fluid management should be conducted, together with life-cycle and social cost–benefit analyses for all 12 hotspot zones—both prerequisites for investment-ready development. Finally, geothermal-specific regulations modelled on EU RED III and tailored to the study area should be developed, with accompanying frameworks to encourage private sector participation and concessional financing.

### Forward-looking research priorities

Five emerging directions warrant priority attention: (i) AI-driven probabilistic reservoir mapping applied to aeromagnetic and gravity data; (ii) Enhanced geothermal systems feasibility assessment at blocks 1, 27, and 36, where TGE architecture favours shallow stimulation; (iii) CO<sub>2</sub> plume geothermal integration with Bida Basin Cretaceous sandstones under Nigeria's NDC Article 6 framework; (iv) satellite thermal infrared screening of hotspot zones using Landsat 8/9 TIRS and ECOSTRESS as a cost-effective pre-drilling tool; and (v) development

of a Pan-African TGE geothermal atlas covering analogous intracratonic basin-margin settings across West and Central Africa, built on FAIR-compliant open-access data.

## Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

## Glossary

|                                           |                                                                                                                                                                                                                                                                                                                                                                                                                     |
|-------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Transitional Geological Environment (TGE) | Basement–sediment contact zone (intracratonic rift or basin-margin); dual conductive + advective heat transfer. No SI unit — geological classification. Bida Basin–Precambrian Basement Complex boundary, Egbako–Share axis. Stable craton: conduction only, GTG < 15 °C km <sup>-1</sup> , HF < 50 mW m <sup>-2</sup> . Oceanic crust: hydrothermal, HF > 100 mW m <sup>-2</sup> , inaccessible for land drilling. |
| Low-enthalpy resource                     | Subsurface fluid temperature < 100 °C at point of extraction. Suitable for direct-use only (heating, GSHP, aquaculture). Projected reservoir T: 40–80 °C at 1,000–3,500 m depth at hotspot zones. Medium-enthalpy: 100–150 °C (binary power). High-enthalpy: > 150 °C (flash/dry steam power).                                                                                                                      |
| Curie Point Depth (CPD)                   | Depth to the 580 °C isotherm (Curie temperature of magnetite). Unit: km. 25.56–46.11 km; mean 37.79 ± 5.84 km. Shallow CPD = hotter crust (geothermal potential). Deep CPD = cooler, stable crust.                                                                                                                                                                                                                  |
| Geothermal Gradient (GTG)                 | Rate of temperature increase with depth. Unit: °C km <sup>-1</sup> (= K km <sup>-1</sup> ). Global continental avg: 25–30 °C km <sup>-1</sup> . 12.58–22.69 °C km <sup>-1</sup> ; mean 15.73 ± 2.41 °C km <sup>-1</sup> . Stable craton: < 15 °C km <sup>-1</sup> . Oceanic spreading centre: > 80 °C km <sup>-1</sup> . TGE: 15–40 °C km <sup>-1</sup> .                                                           |
| Heat Flow (HF)                            | Thermal energy flux from Earth's interior. Unit: mW m <sup>-2</sup> . Global continental avg: ~60 mW m <sup>-2</sup> . 31.45–56.73 mW m <sup>-2</sup> ; mean 39.33 ± 6.12 mW m <sup>-2</sup> . TEG low-enthalpy viable: 40–80 mW m <sup>-2</sup> . High-enthalpy: > 80 mW m <sup>-2</sup> . Oceanic: > 100 mW m <sup>-2</sup> .                                                                                     |
| Thermal Conductivity (λ)                  | Rock's ability to conduct heat. SI unit: W m <sup>-1</sup> K <sup>-1</sup> (= W m <sup>-1</sup> °C <sup>-1</sup> , numerically equivalent). 2.5 W m <sup>-1</sup> K <sup>-1</sup> assumed uniform (avg. igneous rocks). Sedimentary rocks: 1.5–2.0 W m <sup>-1</sup> K <sup>-1</sup> (lower; introduces uncertainty in basin areas).                                                                                |

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## Author contributions

T. A. A.: designed the study, co-supervised the study, did the data analysis, modelling and interpretation, approved the draft manuscript, revised the entire manuscript for submission; S. A. S.: conceptualised the study, did the data analysis, modelling and interpretation, wrote the draft manuscript, revised the second draft; K. O. S.: provided the technical support, handled the literature review and revision of the manuscript; L. A. S.: supervised the study, reviewed all the analysis and interpretation stages, approved the draft manuscript, revised the entire manuscript for submission; M. A., N. K. S., & S. I.: assisted in data interpretation, handled the second draft and revision of the manuscript; MAI & IJA: offered professional advice and assisted in the major revision window.

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## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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