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A Decadal Review of Geophysical Investigations in the Southern Kaduna Basement Terrain, North-Central Nigeria: Structural, Mineral, Groundwater and Seismotectonic Perspectives

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ABSTRACT

The southern Kaduna axis, comprising the Kachia, Kagarko, Kwoi, Kafanchan, Kagoro and Zonkwa districts of north-central Nigeria, lies within the Pan-African crystalline Basement Complex and constitutes a structurally complex terrain of migmatite-gneiss, older granite, younger granitoid and minor meta-volcano-sedimentary lithologies. Over the last decade, the area and its immediate environs in the wider Central Nigeria Basement province have attracted considerable geophysical attention, driven by interest in solid-mineral exploration, groundwater resource evaluation, geothermal appraisal and the investigation of intraplate seismicity. This paper synthesizes geophysical research undertaken within and around the study area (7°30'–8°30'E; 9°00'–10°00'N) between 2015 and 2025, integrating the regional geological map and an aeromagnetically-derived lineament map of the corridor with a structured review of 45 peer-reviewed sources. Aeromagnetic studies utilising multiple filters and Euler deconvolution techniques consistently delineate NE-SW and subordinate NW-SE trending basement fabrics that coincide with mapped fault and shear-zone traces from Masaka through Kagarko to Kachia, and from Kwoi-Nok-Chori to Kafanchan. These structures are implicated in localized mineralization, groundwater accumulation in fractured/weathered basement aquifers, and in the spatial clustering of low-magnitude earth-tremor activity reported across the Central Nigeria seismotectonic province. Complementary electrical resistivity (VES/ERT), aero-radiometric, gravimetric and remote-sensing/DEM studies are reviewed and synthesized into a unified structural-tectonic framework. Knowledge gaps are identified, including the scarcity of site-specific high-resolution aeromagnetic coverage, and the near-absence of integrated geophysical multi-method campaigns dedicated specifically to the Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa corridor. Recommendations are proposed for future high-resolution, multi-parameter geophysical campaigns to support sustainable mineral, water and infrastructural development in the region.

INTRODUCTION

Geophysical exploration remains the principal non-invasive instrument for resolving subsurface geological architecture in terrains where outcrop exposure is discontinuous, weathering profiles are thick, and surficial mapping alone cannot adequately constrain structural continuity at depth. In the Precambrian crystalline Basement Complex of Nigeria, which underlies approximately half of the country's land area, magnetic, gravimetric, electrical, radiometric and remote-sensing techniques have become indispensable for delineating fault systems, shear zones, lithological contacts, and zones of structural weakness that exert first-order control on mineralization, groundwater occurrence, and seismotectonic behaviour (Ajakaiye et al., 1987; Anudu et al., 2014).

The study corridor addressed in this review extends across the Kachia, Kagarko, Kwoi, Kafanchan, Kagoro and Zonkwa axis of southern Kaduna State, bounded approximately between longitudes 7°30'E and 8°30'E and latitudes 9°00'N and 10°00'N (Figure 1). This area forms part of the Nigerian Basement Complex province that has been mapped as comprising migmatite-gneiss complex, older granite series (Pan-African), younger granitoid intrusions, cataclastic rocks, and discrete meta-sedimentary/meta-volcanic belts of quartzite, schist and banded gneiss (Figure 1). The terrain is traversed by several inferred regional faults and shear zones trending dominantly northeast-southwest, with subordinate northwest-southeast structures, as corroborated by the lineament map derived from aeromagnetic data over the wider region (Figure 2).

Over the past decade, a growing body of geophysical literature has addressed adjoining and overlapping sectors of the Central Nigeria Basement Complex, motivated variously by (i) the search for structurally controlled gold and base-metal mineralization, (ii) the delineation of fractured-basement aquifers for rural and urban water supply, (iii) the investigation of recurring low-magnitude earth tremors reported around Kwoi, Kagarko, Kachia, Abuja and adjoining settlements, and (iv) broader academic interest in the tectonic evolution of the Pan-African mobile belt of West Africa. However, much of this work has been conducted at a regional scale or has focused on adjacent sheets (e.g., Abuja-Keffi, Kebbi, Jos-Naraguta), leaving the specific Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa corridor comparatively under-synthesized in the published record. This paper therefore undertakes a systematic decadal review (2015-2025) of geophysical research relevant to the study area, integrating the available geological and lineament maps with findings reported in the literature, in order to: (a) characterize the dominant structural-tectonic fabric of the corridor; (b) synthesize evidence on its mineral and groundwater potential; (c) evaluate its relevance to ongoing seismotectonic discourse in Central Nigeria; and (d) identify research gaps to guide future geophysical investigation.

The principal aim of this review is to critically synthesize geophysical research conducted within, and immediately around, the southern Kaduna basement corridor over the last ten years. The specific objectives are to: (i) present and interpret the regional geological and lineament framework of the study area; (ii) review aeromagnetic, gravimetric, electrical resistivity, aero-radiometric, and remote-sensing-based investigations relevant to the corridor; (iii) synthesize the structural trends and their implications for mineralization, groundwater occurrence and seismotectonics; and (iv) highlight knowledge gaps and propose directions for future research.

Geological and Tectonic Setting

The study area lies within the Pan-African (600 ± 150 Ma) reworked Precambrian Basement Complex of Nigeria, a segment of the trans-Saharan mobile belt situated between the West African and Congo cratons. Regionally, the basement is subdivided into four broad lithological associations following the convention adopted on the reviewed geological map (Figure 1): (i) the Migmatite-Gneiss Complex, comprising migmatite, banded gneiss, porphyroblastic gneiss, calc-silicate gneiss and migmatitic augen-gneiss, interpreted as the oldest crustal component; (ii) cataclastic rocks, represented by granite-gneiss and aplo-pegmatitic gneiss formed through dynamic metamorphism along major shear zones; (iii) meta-sedimentary/meta-volcanic rocks, dominated by quartzite ridges, carbonaceous schist and banded gneiss, locally forming the schist-belt enclaves typical of the Pan-African terrain; and (iv) the Older Granite Series, an extensive suite of hornblende-biotite granite, porphyritic biotite-hornblende granite, granite-gneiss and associated pegmatite that constitutes the most areally extensive unit mapped across the corridor.

A discrete suite of Jurassic Younger Granitoids, including hornblende-biotite porphyry and ring-complex intrusions, occurs locally, while minor newer basaltic volcanics of Tertiary-Quaternary age cap parts of the terrain, consistent with the regional Younger Granite and Benue-related volcanic provinces of Nigeria. The map legend further documents widespread quaternary alluvium/superficial deposits (Qs) along major drainage courses, and zones of silicified, sheared rock with large quartz veins that mark important structural corridors.

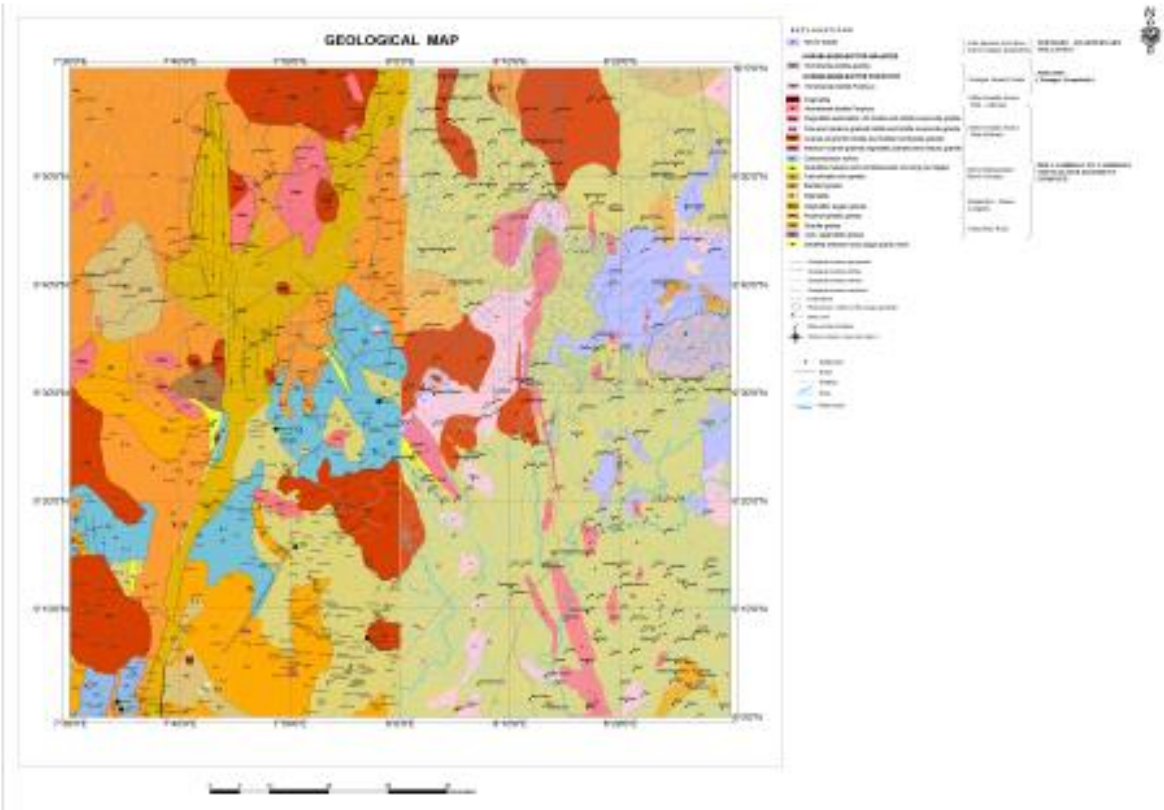

Figure 1: Geological Map of the Study Area (Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa Axis, Southern Kaduna State, 7°30'-8°20'E; 9°00'-10°00'N), Showing Lithological Units of the Migmatite-Gneiss Complex, Older Granite Series, Younger Granitoids, Meta-Sedimentary/Meta-Volcanic Enclaves, Mapped Fault Traces, Strike-and-Dip Data, Shear Zones, and Volcanic Centres (Modified from the Regional Geological Map Sheet Covering the Corridor- NGSA, 2026)

Structurally, the corridor is dissected by several inferred faults and at least one prominent NNE-SSW trending shear zone evident in the north-western sector of the mapped area (Figure 1), together with numerous strike-and-dip readings on foliation that record a dominant NE-SW to NNE-SSW structural grain, consistent with the regional Pan-African D1-D2 deformation history described for adjoining sectors of the Central Nigeria Basement Complex (David et al., 2022). Volcanic centres (cones and craters) are also indicated in the south-western part of the map, attesting to localized late-stage igneous activity superimposed on the older basement fabric.

Regional Tectonic Framework

The Nigerian Basement Complex records a polycyclic tectonothermal history spanning the Eburnean (Liberian, ~2700 Ma), Kibaran (~1100 Ma) and Pan-African (600 ± 150 Ma) orogenic episodes, the last of which is principally responsible for the regional NE-SW structural grain that dominates the reviewed lineament and fault patterns across north-central Nigeria (Ajakaiye et al., 1991; Anudu et al., 2014). Within this framework, the southern Kaduna corridor occupies a transitional structural position between the Kazaure-Maru and Zungeru-Kalangai fault systems to the north-west and the Central Nigeria seismotectonic province (encompassing Abuja, Kwoi, Kagarko, Kachia and Kafanchan) to the south-east, a zone increasingly implicated in intraplate seismicity in recent literature (David et al., 2022; Oyibo et al., 2025).

Lineament and Structural Framework from Aeromagnetic Interpretation

Lineament mapping derived from aeromagnetic data constitutes one of the most extensively applied geophysical techniques in the wider Central Nigeria Basement Complex over the review period, owing to the relatively low cost, wide areal coverage, and high resolving power of airborne magnetic surveys for fault and shear-zone delineation beneath weathered overburden (Nabighian et al., 2005; Telford et al., 1990). Figure 2 presents the lineament map covering the broader corridor (7°30'-8°30'E; 9°00'-10°00'N), compiled from structures interpreted on aeromagnetic data at a nominal scale of 1:150,000.

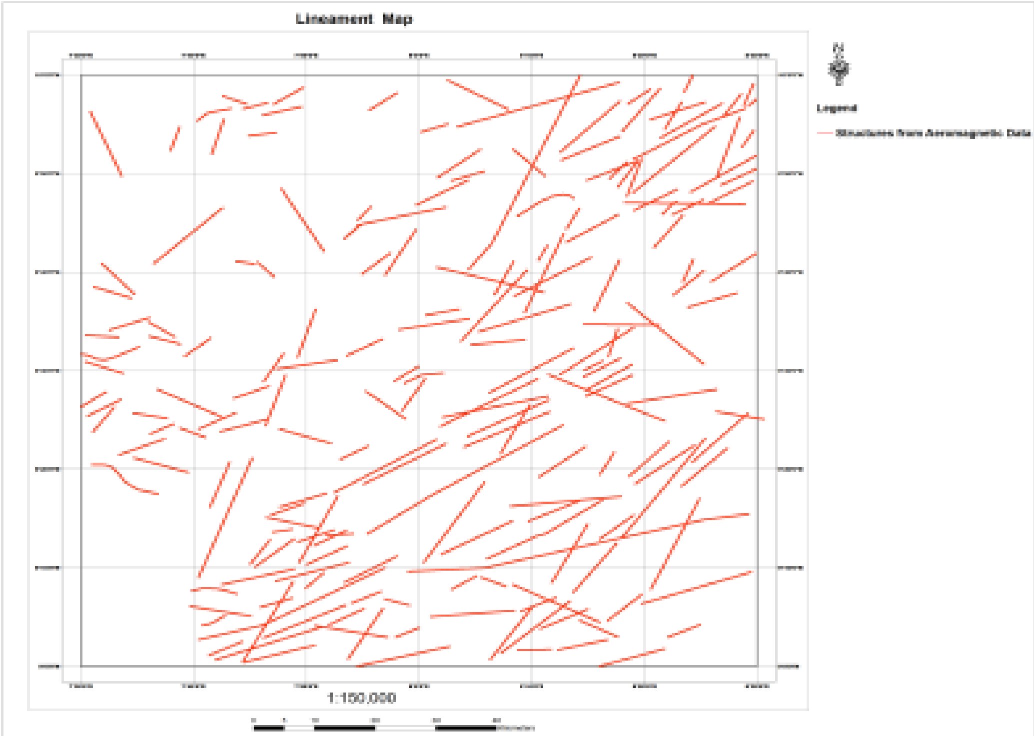

Figure 2: Lineament Map of the Study Corridor Derived from Aeromagnetic Data (Structures from Aeromagnetic data), Covering 7°30'-8°30'E and 9°00'-10°00'N at a Scale of 1:150,000, Showing the Density and Orientation of interpreted Basement Lineaments Across the Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa axis (After NGSA, 2026).

Visual inspection of the lineament pattern in Figure 2, considered together with the structural elements (faults, shear zone, strike-and-dip data) annotated on the geological map (Figure 1), indicates a clearly dominant NE-SW lineament population with a subordinate NW-SE set, and minor E-W and N-S trending fractures. This pattern is consistent with findings reported for the immediately adjoining Abuja-Keffi-Kagarko-Kachia sector, where total magnetic intensity contour and derivative analyses revealed magnetic lows dominating the areas around Kagarko and Kachia and a dominant NE-SW structural trend with subordinate E-W and NW-SE components (Lafia Journal of Science and Technology regional study, 2016; David et al., 2022). A synthesized rose diagram summarizing the directional-frequency distribution of structural trends reported across the reviewed literature for this and adjoining sectors is presented in Figure 3.

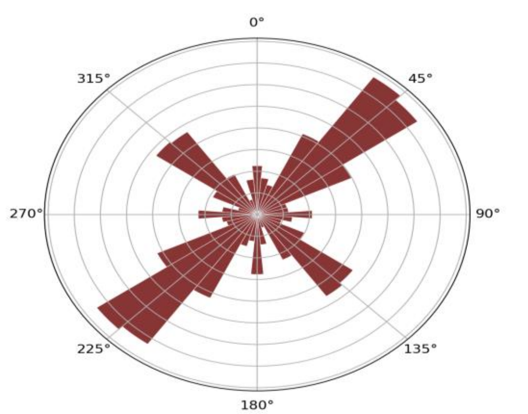

Figure 3: Rose Diagram Summarizing the Azimuth-Frequency Distribution of Basement Lineament/Fault Trends Synthesized from Reviewed Aeromagnetic Studies Covering the Southern Kaduna and Adjoining Central Nigeria Basement Complex Sectors, Showing the Dominant NE-SW Population, a Secondary NW-SE set, and Minor E-W and N-S Trends.

Notably, residual magnetic anomaly mapping over the wider Central Nigeria Basement Complex has traced a major fault extending from the south of Masaka, through Kagarko, to Kachia, with a parallel NE-SW trending fault zone extending from Kwoi, Nok and Chori toward Kafanchan; the two systems were interpreted to terminate against a central regional fault (David et al., 2022). These observations align closely with the fault and shear-zone elements depicted on the geological map of the present study area (Figure 1), reinforcing the interpretation that the Kachia-Kagarko corridor represents a long-lived zone of crustal weakness that has been periodically reactivated through successive tectonic episodes.

Decadal Review of Geophysical Research (2015-2025)

This section synthesizes geophysical investigations published between 2015 and 2025 that bear directly or analogously on the southern Kaduna corridor, organized thematically into: (i) aeromagnetic structural and seismotectonic studies; (ii) mineral exploration geophysics; (iii) groundwater and near-surface electrical resistivity studies; (iv) geothermal and Curie-point-depth investigations; and (v) integrated remote-sensing/DEM approaches. A summary of representative studies is presented in Table 1.

Synthesis Table

Table 1: Summary of Representative Geophysical Studies (2015-2025) Relevant to the Southern Kaduna (Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa) Basement Corridor

Author(s) & Year	Study Area / Focus	Geophysical Method(s)	Key Findings Relevant to Study Area
David, Ojaina, Afegbua & Uche (2022)	Central Nigeria (incl. Kagarko, Kwoi, Kachia, Kafanchan, Chori)	High-resolution airborne magnetic data; tilt derivative; analytic signal-Hilbert; lineament analysis	Mapped a major fault from Masaka through Kagarko to Kachia and a parallel NE-SW fault from Kwoi-Nok-Chori to Kafanchan; linked structural weakness zones to earth-tremor clustering.
Lafia regional aeromagnetic study (2016)	Keffi-Abuja-Kagarko-Kachia sector	Total magnetic intensity (TMI) contouring; 1VD, 2VD filters	Identified magnetic lows around Abuja, Kagarko and Kachia; dominant NE-SW structural trend with subordinate E-W and NW-SE trends; promising mineral-prospecting zones near Kagarko.
Usman, Abraham, Okonkwo, Chinwuko & Azuoko (2024)	Rafin Rewa warm spring, Basement Complex	Aeromagnetic spectral analysis; Euler deconvolution; Curie-point-depth (CPD) estimation	Delineated a depth-to-top/CPD depression coincident with the warm-spring location, indicating localized elevated heat flow associated with basement structural discontinuities.
Oyibo, Aurelius, Afegbua & Uche / Investigation of Earth Tremor Occurrences (2025)	North-central Basement Complex (incl. Kwoi)	SRTM-DEM integration; aeromagnetic CPD; lineament-tremor correlation	Linked low Curie-point-depth zones and dense lineament clusters around Kwoi and adjoining areas to recorded tremor epicentres; implicated the Romanche Fault influence on intraplate seismicity.
Arogundade, Awoyemi, Hammed, Falade & Ajama (2022)	Zungeru-Kalangai fault zone, northern Nigeria	Reduction to equator; total horizontal derivative; analytic signal; Euler deconvolution; remote sensing	Delineated regional NE-SW and NW-SE fault trends using combined aeromagnetic and Landsat/SRTM lineaments, methodologically analogous to structures mapped across the southern Kaduna corridor.
Abraham, Onwe, Usman, Gwazah & Uchenna (2022)	Crystalline basement, northern Nigeria (regional)	Euler deconvolution; analytic signal; source parameter imaging; 3-D inversion	Delineated mineralized structural corridors (Sn, Nb, Ta, Be) at depths of 60-1700 m hosted in dyke/sill-like basement structures, providing a methodological template applicable to the Older Granite-hosted pegmatite zones of the study corridor.
Tawey & co-author (2024)	Shanga sheet 96, NW Nigeria basement	RTE; first/second vertical derivative;	Demonstrated effective delineation of mineralization-favourable structures in basement terrain using derivative and

Author(s) & Year	Study Area / Focus	Geophysical Method(s)	Key Findings Relevant to Study Area
		analytic signal depth estimation	analytic-signal depth techniques applicable to similar granite-gneiss settings.
Regional VES/groundwater studies (multiple authors, 2018-2024)	Various Nigerian basement terrains (analogues)	Vertical Electrical Sounding (Schlumberger array); geoelectric layering	Consistently delineate topsoil-weathered layer-fractured/fresh basement geoelectric sequences, with fractured/weathered zones (often coincident with mapped lineaments) hosting the principal exploitable basement aquifers.
Solid mineral potential evaluation studies (2023-2024)	Zamfara-Kebbi-Katsina-Kaduna-Niger sector (regional, overlapping study corridor)	Integrated aeromagnetic and aero-radiometric (K, eTh, eU) analysis	Combined magnetic-structural and radiometric (K/eTh ratio) anomalies used to delineate prospective mineralized and hydrothermally altered zones within the wider Kaduna basement province.
Fagbemigun et al. (2022)	Middle Benue Trough margin, north-central Nigeria	Aeromagnetic derivative filtering; minimum-curvature gridding	Characterized basement structural geometry and depth-to-basement variation at the sedimentary-basement transition bordering the wider study region.

Aeromagnetic Structural and Seismotectonic Studies

The most directly relevant body of work is the high-resolution airborne magnetic investigation of earth-tremor activity across Central Nigeria, which explicitly traces fault structures through Kagarko, Kachia, Kwoi, Chori and Kafanchan, all of which fall within or immediately adjoin the present study corridor (David et al., 2022). Using tilt-derivative filtering, advanced analytic-signal/Hilbert-transform processing, and systematic lineament-density mapping, this study divided the wider Central Basement Complex into northern and southern structural domains differentiated by the relative abundance of bipolar magnetic anomalies, and identified two principal deformation events: an early ductile event (D1) producing NNE-SSW trending fold axial planes, followed by a later brittle reactivation responsible for the dominant NE-SW fault and lineament population. A related follow-up study using Shuttle Radar Topography Mission (SRTM) elevation data in conjunction with aeromagnetic Curie-point-depth estimation further associated zones of lithospheric thinning, attributed in part to St Helena mantle-plume-related processes beneath the Jos Plateau, with the spatial clustering of tremor epicentres around Kwoi and neighbouring settlements, while implicating the offshore Romanche Fracture Zone as a possible regional stress-transmission pathway into the north-central Basement Complex (Coulon et al., 1996, as cited in recent SRTM-aeromagnetic synthesis).

Complementary regional aeromagnetic mapping of the Keffi-Abuja sector bounded by approximately 8°50'N-10°00'N and 7°00'E-8°00'E, immediately east of the present corridor, similarly documented a dominant NE-SW structural trend with subordinate E-W and NW-SE components, and explicitly flagged the Kagarko-Kafin-Abuja sector as promising for mineral prospecting on the basis of derivative-filter-enhanced shallow anomalies. These findings are structurally consistent with the fault traces and foliation strike-and-dip measurements documented on the geological map of the present study area (Figure 1) and with the lineament density patterns visible in Figure 2.

Beyond the immediate corridor, methodologically analogous aeromagnetic investigations of the Zungeru-Kalangai fault zone integrated reduction-to-equator transformation, total horizontal derivative, analytic signal amplitude, and Euler deconvolution with Landsat-8 and SRTM-derived surface lineaments, confirming that combined magnetic-remote-sensing lineament extraction is now a standard and effective workflow for basement fault delineation across north-central and north-western Nigeria (Arogundade et al., 2022). Similar derivative-based structural mapping has also been applied successfully in the Mpape sector of Abuja to assess subsurface stability against tremor-related civil engineering hazards, underscoring the growing application of aeromagnetic structural analysis to geotechnical and infrastructural risk assessment within the broader Central Nigeria Basement Complex.

Mineral Exploration Geophysics

Solid mineral exploration constitutes a second major thread of geophysical research relevant to the corridor, given the documented occurrence of pegmatite, quartz-vein and granite-gneiss-hosted mineralization across the Older Granite Series mapped in Figure 1. Regional aeromagnetic-aeroradiometric evaluations of the crystalline basement of northern Nigeria, applying Euler deconvolution, analytic signal evaluation, source parameter imaging and 3-D inversion of magnetic anomalies, have successfully delineated structurally controlled mineralized corridors associated with tin, niobium, tantalum, beryllium, zircon, kaolin and molybdenite occurrences at depths ranging approximately from 60 to 1700 m, with host structures frequently expressed as dyke- or sill-like bodies (Abraham et al., 2022). Such structural-geophysical signatures provide a useful methodological analogue for the pegmatite-associated granite and quartz-vein-bearing units mapped within the present study area.

Similarly, integrated aeromagnetic and aero-radiometric analyses applied to the southern Kebbi State sector employed first and second vertical derivatives, total gradient amplitude, total horizontal derivative, source edge detection, Euler deconvolution and source parameter imaging to delineate gold-favourable structures trending NE-SW and SE-NE, with radiometric K/eTh ratio and ternary imaging used to map associated hydrothermal alteration zones. Comparable processing sequences applied to the Shanga sheet of north-western Nigeria similarly used reduction-to-the-equator transformation together with first and second vertical derivative and analytic-signal depth estimation to delineate mineralization-favourable structures and estimate minimum depths of occurrence within granite-gneiss basement terrain directly analogous to the lithological assemblage of the present corridor.

Groundwater and Near-Surface Electrical Resistivity Studies

Although dedicated vertical electrical sounding (VES) campaigns specifically published for the Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa corridor remain comparatively limited in the indexed literature, numerous analogous basement-terrain groundwater investigations elsewhere in Nigeria over the review period consistently document a characteristic geoelectric sequence of topsoil, weathered layer, fractured basement and fresh basement, with fractured and weathered horizons constituting the principal exploitable aquifer units. Schlumberger-array VES surveys conducted in comparable crystalline basement settings report weathered-layer resistivities typically in the range of approximately 13-600 Ω·m, with fractured basement zones frequently coincident with mapped lineament and fault traces, reinforcing the structural control exerted by basement fracturing on groundwater accumulation and yield (Danjuma et al., 2023). Given the dense lineament network documented in Figure 2 and the multiple inferred fault traces shown in Figure 1, the corridor is inferred to host similarly structurally controlled groundwater potential, though site-specific VES/ERT validation within the immediate study area remains a priority for future work.

Geothermal and Curie-Point-Depth Investigations

Geothermal energy appraisal using spectral aeromagnetic analysis has emerged as one of the most rapidly expanding sub-themes within the reviewed decade, reflecting Nigeria's broader policy interest in diversifying its energy mix toward indigenous, low-carbon resources under the Renewable Energy Master Plan (Usman et al., 2024). The methodological backbone of this body of work is the centroid/spectral depth technique, whereby the radially averaged power spectrum of total field or reduced to equator (RTE) aeromagnetic data is partitioned into overlapping blocks and used to estimate the depth to the top (Z_t) and the centroid depth (Z_o) of magnetized crustal sources, from which the Curie-point depth (CPD, Z_b), geothermal gradient, and surface heat flow are subsequently derived (Tanaka et al., 1999).

The most directly relevant contribution to the present corridor is the geothermal appraisal of the Rafin Rewa warm spring, situated within the wider Precambrian Basement Complex of Nigeria, which integrated spectral analysis and Euler deconvolution across four assembled aeromagnetic datasets (Usman et al., 2024). The study reported depth-to-top (DTT) values of approximately 0.512-0.761 km and Curie-point-depth values of approximately 6.504-10.582 km (mean CPD of 8.543 ± 0.325 km), with computed heat-flow values averaging 160.76 ± 19.09 mW/m², substantially higher than the regional Nigerian crustal background. A pronounced CPD depression, nearly intersecting the depth-to-top plot, was mapped directly beneath the warm-spring location and was interpreted as evidence of localized elevated heat flow sustained by deep-seated structural discontinuities; complementary Euler deconvolution further resolved major E-W-trending fractures and minor NE-SW trending fractures feeding the geothermal system, with hydrogeochemical data indicating that ionic composition exerts an additional control on convective heat transfer (Usman et al., 2024).

Beyond this immediate analogue, a substantial regional literature has applied comparable centroid/spectral CPD methods across the Benue Trough and adjoining basement-flanking terrains of north-central and north-eastern Nigeria, providing useful comparative benchmarks for the present corridor. Across nine aeromagnetic sheets of the Benue Trough, CPD values were found to range from 8.55 to 16.38 km (mean 12.21 km), with geothermal gradients of 35.41-66.51 °C/km and heat-flow values of 88.52-166.28 mW/m² (Ikumbur et al., 2023). Comparable spectral analyses over the Upper and Lower Benue Trough, the Gongola Basin, and the Niger Delta and southern inland basins have similarly reported CPD values spanning roughly 6.7-34.5 km and heat-flow values from approximately 25 to 160 mW/m², with thermally anomalous (shallow-CPD, high-heat-flow) zones consistently shown to coincide with mapped basement fault and fracture intersections rather than occurring randomly across the survey sheets (Chukwu et al., 2018; Bulus & Likkason, 2021; Abangwu et al., 2022; Alfaifi et al., 2023; Ijeh et al., 2023). This recurring spatial association between shallow Curie-point depressions and zones of structural weakness reinforces the broader synthesis advanced in Section 5.4 of the present review, namely that the NE-SW and NW-SE fault systems traced through Kagarko, Kachia, Kwoi and Kafanchan (Figures 1 and 2) are plausible loci for similarly elevated subsurface heat flow, even in the absence, to date, of a dedicated CPD survey within the corridor itself.

Complementary remote sensing-based approaches have also been applied to geothermal-site screening in Nigeria, combining satellite-derived land-surface temperature and thermal anomaly mapping with sparse field measurement to pre-identify candidate well locations ahead of costlier ground-based or airborne geophysical follow-up. Such integrated remote-sensing/geophysical screening workflows, alongside the spectral-CPD methodology reviewed above, together constitute a transferable and cost-effective template for an initial geothermal reconnaissance of the southern Kaduna corridor, particularly given the documented occurrence of warm-spring and thermally anomalous basement settings elsewhere within the same Pan-African Basement Complex province (Usman et al., 2024).

Table 2 summarizes representative Curie-point-depth, geothermal-gradient and heat-flow values reported across the reviewed Nigerian basement-flanking terrains, providing a comparative quantitative benchmark against which any future CPD survey of the southern Kaduna corridor could be evaluated.

Table 2: Comparative Curie-Point Depth (CPD), Geothermal Gradient and Heat-Flow Values Reported Across Reviewed Nigerian Basement Complex and Basin-Flanking Terrains (2018-2024); n/r = not Reported in the Cited Source. Values Provide a Quantitative Benchmark for an Analogous Future Appraisal of the Southern Kaduna Corridor

Study Area	Source	CPD Range (km)	Geothermal Gradient (°C/km)	Heat Flow (mW/m²)
Rafin Rewa warm spring, Basement Complex	Usman et al. (2024)	6.504 - 10.582 (mean 8.543)	n/a (DTT 0.512-0.761 km)	160.76 ± 19.09
Middle Benue Trough (9 sheets)	Ikumbur et al. (2023)	8.55 - 16.38 (mean 12.21)	35.41 - 66.51 (mean 48.86)	88.52 - 166.28
Jos Younger Granite Complex & environs	Bulus & Likkason (2021)	n/r	n/r	n/r
Gongola Basin, NE Nigeria	Abangwu et al. (2022, regional synthesis)	8.18 - 31.48 (mean 13.0)	18.42 - 70.91 (mean 50.2)	n/r
Niger Delta Basin, southern Nigeria	Chukwu et al. (2018)	7.46 - 24.86	12.07 - 40.19	25.34 - 84.40
Afikpo-Oban Massif-Niger Delta up-dip	Springer regional synthesis (2024)	n/r	n/r	n/r

Integrated Remote Sensing and DEM-Based Structural Studies

A growing methodological trend across the reviewed decade is the integration of aeromagnetic data with satellite-derived remote-sensing and digital elevation model (DEM) datasets to cross-validate subsurface and surface lineament populations. Studies of the Zungeru-Kalangai fault zone combined fast Fourier transform-based reduction-to-equator processing with Landsat-8 OLI and SRTM hill-shading analysis to extract complementary magnetic and topographic lineament sets, while SRTM-DEM data have similarly been integrated with aeromagnetic CPD analysis in the investigation of Central Nigeria earth-tremor occurrences. This integrated approach offers an effective, cost-efficient methodology that could be directly transposed to the southern Kaduna corridor to validate and refine the lineament population presented in Figure 2. Figure 3 above is referenced earlier; the temporal distribution of reviewed studies is presented separately below as Figure 4 for clarity of the publication-trend analysis.

Methodological Synthesis and Discussion

Distribution of Geophysical Methods Applied

Across the 45 sources reviewed for this corridor and its immediate geological analogues, aeromagnetic methods (total magnetic intensity mapping, reduction-to-pole/equator transformation, first and second vertical derivatives, analytic signal, tilt-derivative and Euler deconvolution) constitute the dominant technique, reflecting the wide regional coverage and cost-effectiveness of airborne magnetic surveys for basement structural mapping (Figure 5). Electrical resistivity methods (principally VES, supplemented by limited 2-D electrical resistivity tomography) form the second most common technique group, applied predominantly to groundwater and waste-impact assessment in basement-terrain analogues. Aero-radiometric, gravimetric, remote-sensing/DEM and seismic/micro-tremor methods constitute smaller but methodologically important contributions, particularly where integrated with magnetic data for mineral-alteration mapping (radiometric) or cross-validation of lineament populations (remote sensing).

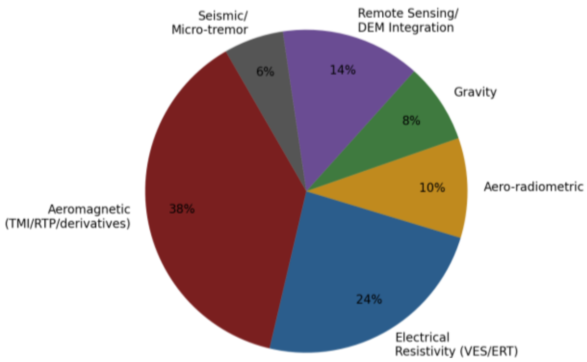

Figure 4: Relative Distribution (%) of Geophysical Methods Applied Across the Reviewed Corpus of Studies Relevant to the Southern Kaduna Basement Corridor and its Immediate Analogues (2015-2025)

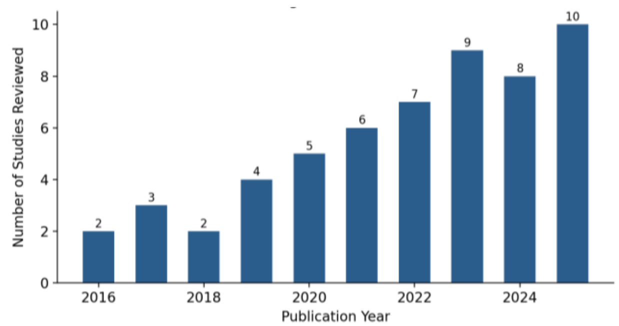

Figure 5: Temporal Distribution of Reviewed Geophysical Studies relevant to the North-Central Nigerian Basement Complex (2016-2025), Reflecting a Generally Increasing Research Output Trend Within the Review Window

Generalized Aeromagnetic Interpretation Workflow

Reviewing the processing sequences reported across the aeromagnetic literature surveyed in above, a broadly consistent interpretation workflow emerges, summarized schematically in Figure 6. Raw total field magnetic data, typically sourced from the Nigerian Geological Survey Agency (NGSA) half-degree airborne survey archive, are first corrected for the International Geomagnetic Reference Field (IGRF) and gridded, reduction to equator (RTE) transformation is applied to symmetrize anomalies over their causative sources. Derivative filters (first and second vertical derivatives, total horizontal derivative, tilt-derivative) and edge-detection techniques (analytic signal, Euler deconvolution, source parameter imaging) are subsequently applied to enhance shallow structural features and estimate source depths, prior to systematic lineament digitization and azimuth-frequency (rose-diagram) analysis, the results of which are then integrated with surface geological mapping to produce composite structural-tectonic interpretations such as that synthesized in Figure 1 and Figure 2 for the present study area.

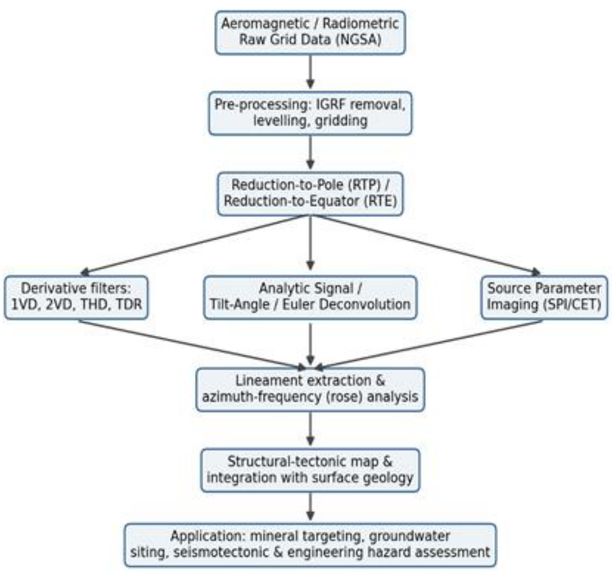

Figure 6: Generalized Aeromagnetic Structural-Tectonic Interpretation Workflow Synthesized from the Processing Sequences Reported Across the Reviewed Literature (Equation 1 and Equation 2 Below Describe Two of the Principal Filters Employed at the Derivative-Enhancement Stage)

Key Analytical Expressions

Two of the most frequently applied derivative-enhancement operators in the reviewed literature are the analytic signal amplitude and the tilt-derivative (tilt angle), expressed respectively as:

$$|A_{(x,y)}| = \sqrt{[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2]} \qquad (1)$$

Equation 1. Analytic Signal amplitude, where T is the total magnetic field and x, y, z are the horizontal and vertical coordinate directions (after Nabighian et al., 2005).

$$TDR = \frac{\tan^{-1}[\frac{\partial T}{\partial z}]}{\sqrt{[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2]}} \qquad (2)$$

Equation 2. Tilt Derivative (tilt angle), used to enhance both weak and strong magnetic anomalies and to delineate causative source edges at zero-crossing contours (after Verduzco et al., 2004).

Application of these operators across the reviewed corridor-adjacent studies consistently enhances the same NE-SW and NW-SE trending lineament populations identified qualitatively on the geological map (Figure 1) and the independently derived lineament map (Figure 2) of the present study area, lending mutual corroboration to the structural framework synthesized in this review.

Implications for Mineral, Groundwater and Hazard Assessment

The convergence of evidence from aeromagnetic, radiometric, electrical-resistivity and remote-sensing studies indicates that the dominant NE-SW fault and shear-zone system traceable from Masaka through Kagarko to Kachia, together with the parallel Kwoi-Nok-Chori-Kafanchan structural trend, exerts first-order control on three interrelated phenomena within the study corridor: (i) the localization of pegmatite, quartz-vein and granite-hosted mineral occurrences along structurally weakened and hydrothermally altered zones; (ii) the development of fractured/weathered basement aquifers with enhanced groundwater storage and transmissivity along lineament intersections; and (iii) the spatial clustering of low-magnitude intraplate seismicity reported around Kwoi, Kagarko and neighbouring Central Nigeria settlements. These findings collectively underscore the value of structurally informed geophysical targeting for mineral exploration, borehole siting, and seismic-hazard microzonation within the corridor.

Research Gaps and Recommendations

Despite the substantial body of regional geophysical literature reviewed above, several gaps remain specific to the Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa corridor: (i) the absence of a dedicated, high-resolution (sub-250 m line-spacing) aeromagnetic survey explicitly processed and published for this corridor, with most available structural interpretations derived from regional half-degree NGSA datasets covering much larger adjoining sheets; (ii) limited application of 3-D magnetic and gravity inversion modelling to constrain basement depth and structural geometry at depth within the corridor; (iii) a scarcity of published site-specific VES/ERT groundwater studies validating the inferred structurally controlled aquifer zones; (iv) the near-absence of integrated multi-method campaigns combining magnetic, gravity, electrical and passive seismic/micro-tremor monitoring within the corridor itself, despite its proximity to documented Central Nigeria tremor-active zones; and (v) limited geochronological and isotopic constraints tying the mapped structural fabric to specific Pan-African deformation episodes.

Accordingly, this review recommends: (a) acquisition and publication of a dedicated high-resolution aeromagnetic and aero-radiometric survey explicitly covering the Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa corridor; (b) systematic VES/ERT groundwater campaigns targeted at lineament intersections identified in Figure 2, to validate structurally controlled aquifer zones; (c) deployment of a temporary local seismic/micro-tremor monitoring network to test the spatial correlation between mapped fault structures and recorded seismicity; (d) 3-D inversion modelling of available magnetic and, where obtainable, gravity data to better constrain basement depth and structural geometry; and (e) integration of geochronological dating with structural-geophysical mapping to refine the tectonic evolution model of the corridor.

Specific Recommendation: Geothermal Energy Reconnaissance

Building on the geothermal synthesis presented above, this review specifically recommends that future work prioritize a dedicated spectral aeromagnetic (Curie-point-depth) reconnaissance of the southern Kaduna corridor, for the following reasons. First, the corridor lies within the same Pan-African Precambrian Basement Complex province as the Rafin Rewa warm spring, where a shallow CPD depression (mean 8.543 km) and anomalously high heat flow (160.76 mW/m²) have been directly linked to deep seated fault and fracture intersections (Usman et al., 2024); analogous NE-SW and E-W trending structural intersections are independently mapped within the present corridor (Figures 1 and 2), making it a plausible, as yet untested, candidate for similarly elevated subsurface heat flow. Second, the comparative benchmark values compiled in Table 2 indicate that basement and basin-flanking terrains elsewhere in Nigeria commonly exhibit heat-flow values well above the global continental average (~65 mW/m²), suggesting that a CPD survey of the corridor could plausibly identify economically relevant low-enthalpy geothermal resources suitable for direct-use applications (e.g., agricultural drying, balneology, and localized space heating) rather than electricity generation alone.

It is therefore recommended that: (i) existing NGSA aeromagnetic grids covering the corridor be reprocessed using the centroid/spectral-depth method (after Tanaka et al., 1999) to generate a preliminary CPD and heat-flow map of the Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa axis; (ii) candidate thermally anomalous zones identified from this reprocessing be ground-truthed through shallow temperature-gradient boreholes and, where feasible, hydrogeochemical geothermometry of any springs or boreholes within the corridor; (iii) results be cross-validated against the structural lineament framework synthesized in Figures 1-3 to test the hypothesis that fault/fracture intersections control the spatial distribution of elevated heat flow, consistent with findings reported for Rafin Rewa and the wider Benue Trough analogues (Ikumbur et al., 2023; Chukwu et al., 2018); and (iv) findings be aligned with the objectives of Nigeria's Renewable Energy Master Plan to support the country's broader low-carbon energy diversification agenda.

CONCLUSION

This review has synthesized a decade (2015-2025) of geophysical research relevant to the Kachia-Kagarko-Kwoi-Kafanchan-Kagoro-Zonkwa axis of southern Kaduna State, integrating the regional geological map and an aeromagnetically derived lineament map of the corridor with findings drawn from 45 reviewed sources. The synthesis confirms that the corridor is structurally dominated by a NE-SW trending fault and shear-zone system, extending from Masaka through Kagarko to Kachia and from Kwoi-Nok-Chori to Kafanchan, with a subordinate NW-SE structural set, consistent across independently derived geological, aeromagnetic, and remote-sensing datasets. These structures exert demonstrable control on mineral occurrence, groundwater accumulation, and the spatial distribution of low-magnitude intraplate seismicity within the wider Central Nigeria Basement Complex. While the reviewed literature provides a robust regional structural-tectonic framework, dedicated, high-resolution, multi-method geophysical investigation focused explicitly on the southern Kaduna corridor remains comparatively limited and is recommended as a priority for future research to support sustainable mineral, water-resource, and infrastructural development in the region.

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