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INTEGRATED GEOPHYSICAL AND GEOLOGICAL STUDY OF CRITICAL STRUCTURAL RELATIONSHIPS INFLUENCING THE OCCURRENCE OF THRUST SYSTEMS, MEGA FOLDS AND STRIKE-SLIP FAULTS IN SOUTHERN NIGERIA SHIELD

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ABSTRACT

The understanding of the structural complexity and development of the Ifewara- Zungeru strike slip fault with other associated tectonic features, such as the Mega Oreke-Okegbo and Okemesi fold, the doubly plunging fold structures and the adjacent thrust belt is yet to be appraised in any publication. These features extend over an area of more than 800 square km and the different aspects of such regional intraplate strike-slip fault and associated structures are fully comprehended with Google Terrain Map and aeromagnetic data interpretation. This study aims to elucidate the critical structural relationships and overprinting relationships influencing the occurrence of the regional strike-slip faults, the folds and the thrust systems. The research provides detailed structural information about the mega Oreke-Okegbo fold and the adjacent thrust duplexes. The former was simply referred to as a shear zone, while the thrust duplexes have not been fully described in terms of nature and implication. The research proposes to produce illustrations and data compilations that will contribute to our knowledge of these structures and the potentiality of the associated mineral resources in this area.

Keywords: Strike-slip fault; Fold belt; thrust duplex; geophysics; tectonic evolution.

INTRODUCTION

When crustal materials are subjected to compressional stress, they compress (get squeezed- bend and fold), if the squeezing and contraction persist for an extended period, crustal materials are uplifted and eventually form reverse and thrust fault systems.Various structural features emerge during a compressional regime, including folds, reverse and thrust faults, imbricate structures, and sheared structures (Homberg *et al.*, 2002; Ogawa and Back, 2022).The development of mega folds and fold-thrust-belts most often occur on large pre-existing fractures. Hence, the formation of the fractures precede the development of the Fold-thrust-belt (Balestra *et al.*, 2019). Part of such major fractures/faults could be obliterated by latter deformations and part could be reactivated with large slips, thus making the interpretation difficult (Homberg *et al.*, 2002). The Ifewara-Zungeru fault, which is the major fundamental fracture hosting the mega folds can hardly be traced continuously at the surface, this also applies to the Oreke-Okegbo mega fold and the thrust structures. Continuous surface trace of these features is almost impossible due to paucity of outcrops and the obliteration of earlier features by latter deformations. The trace of thrust faults and nappe within the Nigerian shield has been speculative due to inadequate surface representation thus necessitating the use of geophysical method for continuous sub-surface trace and confirmation of these structural features . Although, a number of recumbent folds have been recognized and reported around Okemesi folds (Caby, 2001; Bamisaiye and Ajala, 2021) south of the current area of focus. The interpretations from both air-borne magnetic survey and Google terrain maps reveal more complexities that are directly related to thrust faults and mega folds. Both the Okemesi fold and the Oreke-Okegbo are hosted along the Ifewara-Zungeru fault zone (Figure 1). A detail investigation of these features has implication for mineral exploration and earthquake hazard mapping due to their ability to serve as pathways for mineralised fluids and accommodate large slip when triggered. This paper investigates and documents these anomalous NNE-SSW trending regional folds and their association both with the dextral strike-slip Ifewara-Zungeru fault and the thrust faults located within the Egbe–Isanlu Schist belt of the Basement Complex of Nigeria. This work has implications for both the structural and tectonic evolution of the Oreke-Okegbo Fold belt in the Lafiaji–Osi region, north of Okemesi fold. Similarities between the pre- and post-collisional stages of the Brasiliano and the Pan-African Orogenies in terms of structural complexity, the accretion processes, metamorphism and magmatic intrusion will be highlighted in this study. This research benefited from the use of high resolution aeromagnetic in interpreting the 3D geometry and regional kinematics of both near and deep-seated structures within this brittle-ductile shear zone. Thus, highlighting salient thrust-nappe related features that were hitherto unsuspected. Several studies had utilized aeromagnetic data analysis in identifying subsurface features, (e.g. Gray and Mortimer 1996; Gunn, 1997; Robertson *et al.*, 2017; Zhu et.al. 2022a; Zhu *et al.*, 2022b). Regional scale Shear Zone Structures such as shear bands, boudins, flow perturbation folds, and foliations identified using magnetic data are documented in several publications such as Betts *et al.* (2007); Calamita *et al.* (2012); Fontainha *et al.* (2021)

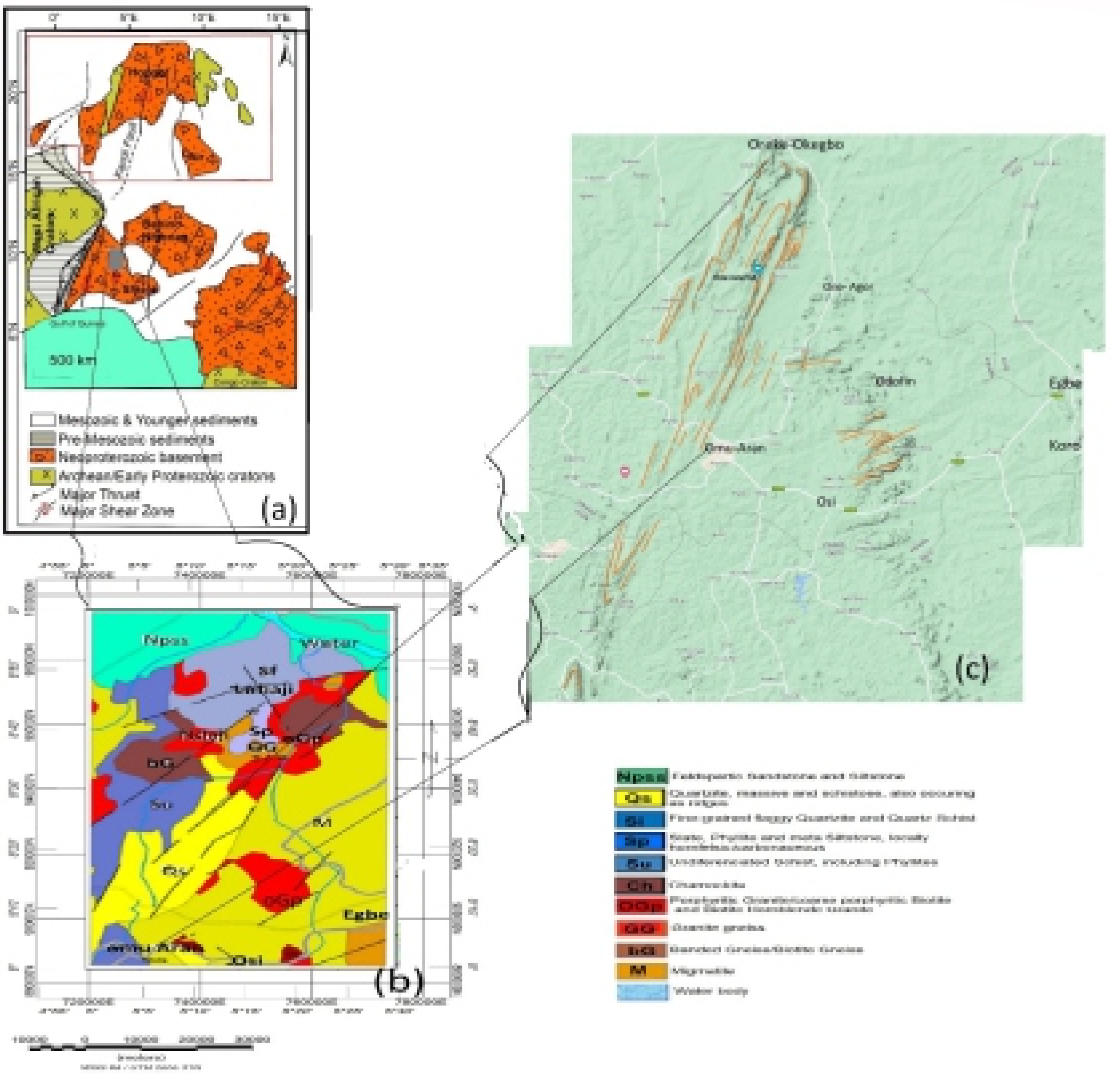


Figure 1: (a) Map showing the Nigerian Shield, the Tuareg and parts of the surrounding cratons. (b) the regional geologic map of the area shows areas from Lokoja to Osi. (c) the Google Map Terrain map shows the Oreke-Okegbo to Okemesi fold belt, the thrust belt in the East, and the interpretations.

GEOLOGY OF THE STUDY AREA

The Lokoja–Osi area (Figure 1b and 1c) is a folded and faulted metasedimetary sequence of quartzite, quarts schist, slate, phyllites and siltstones that were intruded by granitic assemblages and bounded to the west by the Ifewara-Zungeru strike-slip Fault Zone.

The lithology of the northern part of this area around the River Niger is predominantly Nupe sandstones of Maastrichtian age (Adepoju *et al*., 2020). The southern part consists of the migmatite-gneiss and infolded metasedimentary rocks belonging to the Basement Complex rocks of Nigeria that has been affected by the Pan–African Orogeny some 600 million years ago. During the Pan-African Orogeny (600 Ma) most of the pre-existing rocks of Liberian (2700 Ma), Eburnean (2000 Ma) and Kibaran (1100 Ma) orogenies were reworked (Ajibade *et al*., 1987). This also led to the reactivation of most of the structural features of the old polycyclic terrain. These coeval activities that initiate Orogeny within the lithospheric crust are compressional, leading to horizontal shortening of the crust; gravitational instability due to excess weight from mountain thickening and rapid convective flow in the mantle leading to increased heat flow (magma) through the lithospheric weak zones (Kroner, 1977; Moinar and Houseman, 2004). Thus, the Eburnean Orogeny in the Nigerian basement was probably contemporaneous with metamorphism, shortening/compressional deformation, transtensional activities and igneous activities (Ferré et. al., 1996). The Eburnean orogeny is classified as a tectonic period with major granitic intrusions. The Kibaran Orogeny in Nigeria occur with the development of intracontinental Neoproterozoic ensialic plate tectonics (accompanied by more intense folding, thrusting and metamorphism) transits to the Pan-African Orogeny (Odeyemi, 1981). The Pan-African Orogeny produced heterogeneous reworking of the Nigerian terrain through widespread deformation, metamorphism and intrusion of granitoids, reactivation of old structures and the generation of the dominant N–S, NNE-SSW and NE–SW shears such as the Zungeru-Ifewara strike-slip fault.

The possible syn-metamorphic structures, recumbent folding coupled with the development of boudinage, presence of intrusive rocks and crenulation cleavages are the result of Pan-African thrust stacking. Proterozoic metasedimentary rocks were stacked over the basement, which was affected by low-to-medium-grade facies metamorphic conditions. A common phenomenon within the Nigerian shield, for example is the presence of older clasts in metaconglomerate rock that is surrounded/ interlayered with similar younger metasediments. This indicates that the post-tectonic deposition probably continued just before the onset of Pan-African Orogeny and after the metamorphism in the Kibaran Orogeny (Turner, 1983). The Pan-African Orogeny probably obliterated the Kibaran orogeny in places, especially within the schist belt terrain of southwestern Nigeria. Migmatization and infolding of the Kibaran sedimentary deposits must have succeeded the formation of the N-S and NNE–SSW trending Ifewara shear zone associated with gold and other mineralization (Dada, 2008; Garba, 2000). Most part of the study area can be described as remnants of Paleoproterozoic rocks infolded within an Archaean migmatite-gneiss complex during an Eburnean event and was reactivated during the Pan-African event.

MATERIALS AND METHODS

This study establishes the nature, geometry, and mode of occurrence of the structures by integrating the dataset acquired from an aeromagnetic survey and google terrain interpretations, corroborated with a detailed geological review of the Lokoja-Osi area. High-resolution aeromagnetic data (covering Lokoja to Osi area i.e., sheets 203 and 224 of magnetic index map of Nigeria) was obtained from the Nigeria Geological Survey Agency (NGSA, 2006) Fugro Airborne Survey Limited, (a non-proprietary company based in Toronto, Canada) was acquired. The air-borne magnetic data was collected using a 3x-Scintrex CS-3 Cesium Vapour magnetometer and at a flight height of 200 m, scanning interval of 0.1 seconds. The data were corrected for diurnal variation and cultural effects, subjected to MAGMAP stepwise filtering for noise removal, gridded in WGS84 projection and reduced to magnetic equator since the data lies within the equatorial regions with low inclination. The

Reduced to the Equator data provides a magnetic field that is horizontally aligned as most of the source magnetizations are horizontal for this region (Foss, 2020) and can be easily classified into distinctive magnetic units based on the residual magnetic anomalies. The equation for the RTE is given in Equation (1) below. These magnetic anomalies were subjected to more advanced data processing applications such as Vertical derivatives (FVD, Equation (2)), The First derivatives measure the rate of change of magnetic field in the vertical direction by enhancing the resolution of the short-wave component of the magnetic field, while minimizing the long wave component (Nelson (1998); Blackly (1998)). Second Vertical Derivatives (SVD, Equation (3) Reeves, 2005; Bonde *et al.* 2019), The SVD has higher resolving power useful in determining with better resolution the structural trends, boundaries of magnetic rocks and depth to basement (Opara, 2011). Total horizontal Derivative (THD (Equation (4) (Grauch and Johnston, 2002; Pham *et al.*, 2020). Horizontal derivatives will enhance high frequency horizontal variations which are interpreted as geologic fractures or contacts (Kaiser *et al.*, 2013: Muhammad, 2018).

Tilt Derivative is useful in mapping subsurface structures (TDR (Equation (5) Abdelrahman *et al.*, 2024), The Analytical Signal filtering Equation (6) Salem *et al.*, 2002) uses a magnetic and ambient geomagnetic autonomous constraint in filtering discrete magnetic bodies and their edges, thus generating an accurate depth estimation and value over each magnetic source.

Eular Deconvolution (Equation (7)) and Source Edge Detection (SED), using Fast Fourier Transformation processing in Oasis Montag Geosoft software. The Eular Deconvolution is based on the use of a structural index exponential (that corresponds to the rate of decrease of magnetic field with distance for a source point to measuring point), and a spatial window size parameter, that determines the size of the area for each calculation (Munis, 2009).

Reduction to Equator

$$L(\theta) = \frac{[\sin(i) - icos(i).\cos(D-\theta)]^2 X(-cos^2(D-\theta))}{[sin^2(i_a) + cos^2(i_a).cos^2(D-\theta)]X[sin^2(i) + cos^2(i).cos^2(D-\theta)]} \quad \text{Eq. (1)}$$

First Vertical Derivative, FVD = $-\frac{\partial f}{\partial z}$ Eq. (2)

Second Vertical Derivative, SVD =

$$-\left(\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2}\right) \quad \text{Eq. (3)}$$

Total Horizontal Derivative,

$$THD(x,y) = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2} \quad \text{Eq. (4)}$$

where T is the magnetic field intensity, $\partial T/\partial x$ and $\partial T/\partial y$ are the orthogonal derivatives of the magnetic field intensity.

Tilt Derivative, TDR = $\theta = \tan^{-1}\left(\frac{\frac{\partial f}{\partial z}}{\frac{\partial f}{\partial h}}\right)$

where $\frac{\partial f}{\partial h} = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2}$ Eq. (5)

Where θ is the tilt angle, $\frac{\partial f}{\partial x}$, $\frac{\partial f}{\partial y}$, *and* $\frac{\partial f}{\partial z}$

are first–order derivatives of magnetic field f in the x, y and z planes.

Analytic Signal Amplitude, ASA =

$$A(x,y) = \sqrt{\left(\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + \left(\frac{\partial f}{\partial z}\right)^2\right)} \quad \text{Eq. (6)}$$

where A (x,y) is the amplitude of the analytic signal at (x,y) position, f is the observed magnetic anomaly at (x, y), $\partial f/\partial z$ is the vertical derivative of the total magnetic field and $\partial f/\partial x$, $\partial f/\partial y$ are the orthogonal derivatives of the total magnetic field in the x- and y-planes, respectively

3D Euler Deconvolution =

$$(x - x_0)\frac{\partial F}{\partial x} + (y - y_0)\frac{\partial F}{\partial y} + (z - z_0)\frac{\partial F}{\partial z} = \eta(\beta - F) \quad \text{Eq. (7)}$$

here β is the nominal value of the magnetic field and x_0, y_0, z_0 define the source position, which gives the total magnetic intensity field F *measured* at (x, y, z); η, being the structural index, is the most important parameter.

RESULTS AND INTERPRETATION

Reduction to Equator

The Residual magnetic intensity map shows amplitude variation between -55.667 nT/m to 49.605nT/m (after the reduced to the Equator analysis) thus revealing the magnetic highs within the central portions of the interpreted area and magnetic lows mostly in the south. However, low-latitude regions such as this with positive magnetic susceptibility differences are usually characterized by magnetic lows on the RMA map. The reduced-to-Equator analysis helps to emphasize the high magnetic signature of the basement complex terrain in the central and southern parts (Figure 2). While the northern parts show prominently low magnetic anomalies. The low magnetic anomalies characterized by large wavelengths are attributed to the sedimentary basin (Lokoja and Patti formations). This thus indicates weak anomalies in non-igneous magnetic sources and stronger anomalies from both igneous and metamorphic basement rocks with higher magnetic mineral concentration.

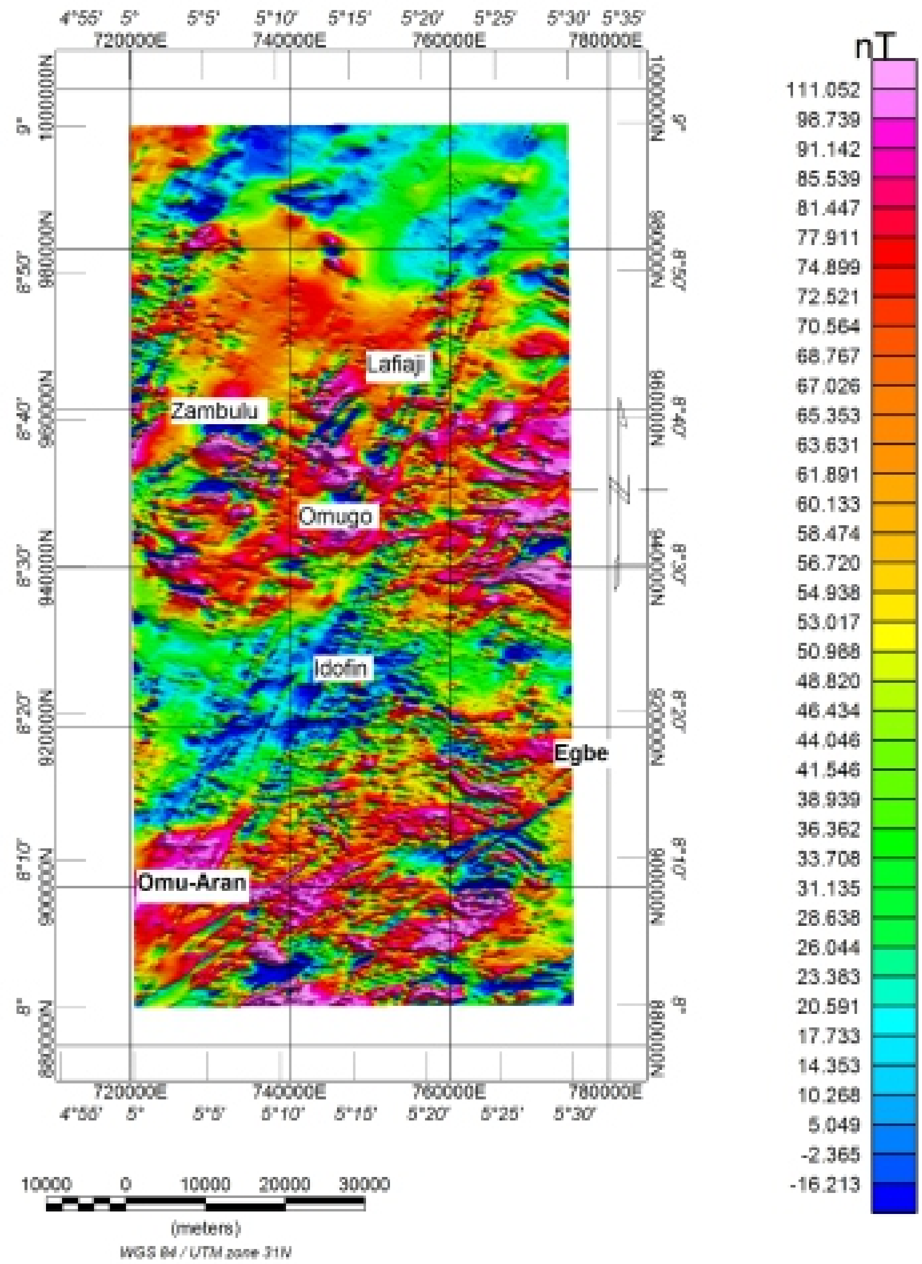


Figure 2: Residual Magnetic Anomaly (RMA) Map after the reduced to equator analysis.

First Vertical Derivative

The First vertical derivative map was produced from the reduced-to-the equator residual magnetic intensity anomaly data and presented in grayscale (Figure 3 and 7(i)). This gives insight into the structural features at crustal levels of the interpreted magnetic anomaly and the degree of variation in the magnetic field in an upright position. This process removes the long and non-vertical features in order to enhance the vertical and most significant features. The investigation also reveal prominent magnetic signatures especially at the center (showing the shear zone, the fold belt region from Oreke-Okegbo to Okemesi and the adjacent thrust stacks in the eastern part from Aran to Egbe (Figure 3). A series of NNE-SSW trending lineaments forming a prominent relief zone coincides with the Ifewara-Zungeru shear zone (Figure 3). The linear features trending NNE-SSW intersect NE-SW trending features at Omu-Aran (Figure 3 and 7(i)). The NE-SW linear features cut across the NNE-SSW in some places. Some of these structural features are absent on both the surface geological map and the Google terrain map but are revealed by the interpreted aeromagnetic data, thus, showing the significance of aeromagnetic data in unveiling hidden subsurface features. The first horizontal derivative (FHD) was used in delineating structures along the horizontal by enhancing the lateral magnetic field contrast.

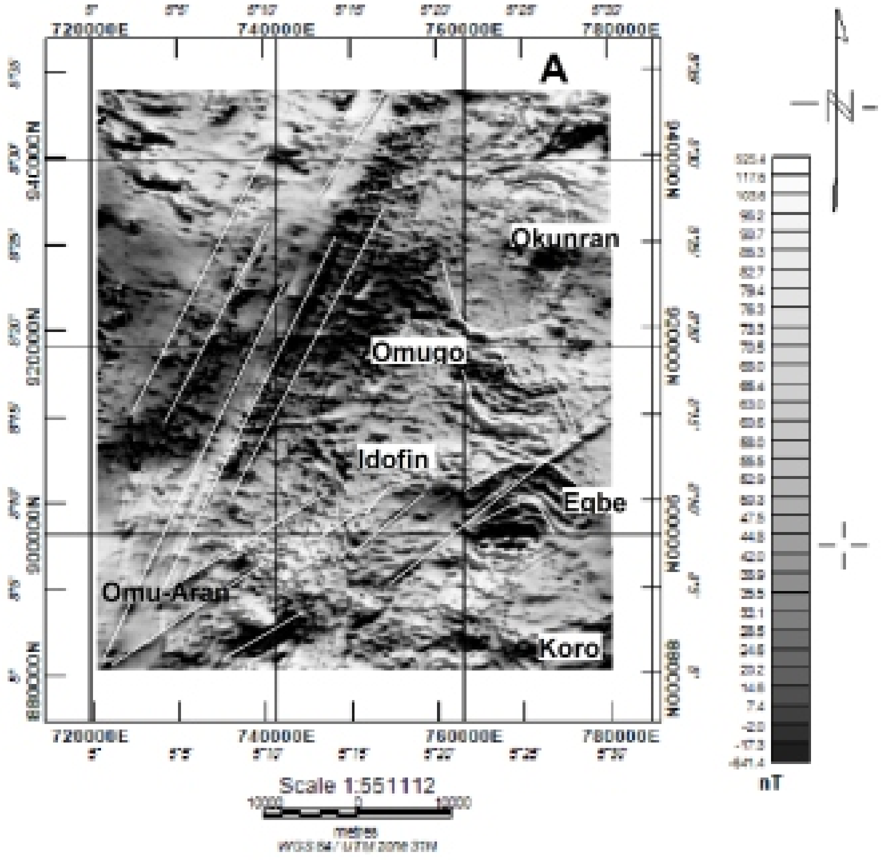


Figure 3: First Vertical Derivative (FVD) of Omu-Aran to Isanlu Okunran area of the interpreted aeromagnetic data. The NNE-SSW trending Ifewara-Zungeru fault and the NE-SW lineaments (A), the Egbe-Anticlinorium and the Koro NW-SE L-S tectonics.

Euler Deconvolution

The geometric form of subsurface magnetic anomaly sources was determined by using the structural index as the key parameter (Munis 2009). Structural index -1 to 2 was evaluated and applied to magnetic anomalies that were previously subjected to Reduce to equator (RTE) analysis. The best results were obtained with a structural index of 0.5 with a spatial window size of 5 km. This structural index of 0.5 was chosen to adequately map the thrust faults and contacts.

Euler deconvolution provides estimates of depth to the magnetic source. It also gives an estimate of sedimentary overburden thickness and approximate depth to the basement. The presence of iron within the sedimentary basin in the northern part is evident. The deepest (approximately >800 m) areas of the Euler deconvolution map are represented with magenta, the shallowest areas are represented with royal blue <100 m depth.

The deepest depth to the basement/ magnetic source occurs in the northern part of the map with clusters in the E-W direction and at the Northwestern part of the map around Zambulu close to the terminal end of the E-W fault (Figures 1b and 4). The southern part of the map is dominated by shallow depth to basement and shallow overburden. These shallow depths show NE-SW linear trend segments that are associated with the thrust system between Omu-Aran and Egbe. These are linked imbricate thrust faults that separate each of the thrust bands as well. Depth of between 300-600 m, oriented in NNE-SSW direction along the Ifewara-Zungeru Shear zone is also noticeable on the Euler map. These are connected with the series of faults that make up the zone and indicates that some of the faults along the Ifewara-Zungeru shear zone (from the Euler solution) go beyond 500 m depth. From the Euler depth solution, certain information about the spatial relationships of ancient topographical surfaces are revealed. Ancient structural highland areas (uplifted regions of the basement) are represented by shallower depths in the south, south-eastern parts and part of the central parts. Most of the paleo-structural low areas (north and west- central part of the map (Figure 4)) are related to a deeper depth such as troughs/ basins/synclines, these correlate with basement/thick sedimentary succession areas.

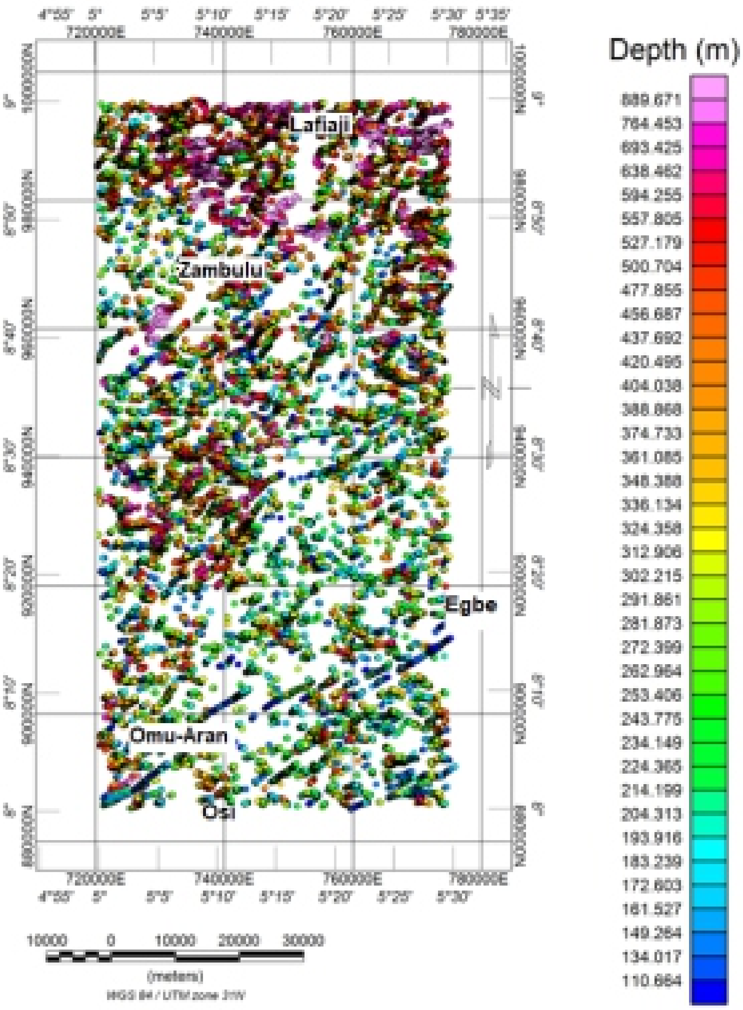


Figure 4: Euler deconvolution map showing the depth to magnetic source in the study area.

Magnetic Intensities and Lithologic Discriminations

Analytical Signal Amplitude

The main sources of magnetic anomalies in the interpreted area are highlighted by the analytic signal map (Figure 5). Weak and featureless characters are synonymous with low magnetic anomalies and are attributed to unmetamorphosed sedimentary rocks within the northern (Npss Figures 1b and 1c), northeastern and northwestern parts. Igneous and metamorphic basement rocks in the southern parts of the RTE and Analytical maps have stronger magnetic anomalies. However, the presence of volcano-sedimentary rocks or shallow depth to basement rocks normally exhibit stronger magnetic anomalies even within the sedimentary basin as seen in the northwestern part of the mapped area. This might be due to the higher volume of magnetic mineral content that dominate the area (Gun, 1997). The Ifewara-Zungeru shear zone is highlighted by strong NNE-SSW trending magnetic signals (Figure 5). Strong undulating magnetic signals dominate the central and far southern parts of the map. These mark the locations of the highest magnetic signals, thus, determining the outlines of magnetic sources. The scattered isolated magnetic anomalies dominate the central part. The trends of the magnetic signal maxima align themselves in the NNE-SSW (Ifewara- Zungeru shear zone), NE-SW (fault lines) and NW-SE direction in the southeastern part. As seen from the analytical signal map, the maximum signals represent the highest magnetic anomalies within the study area.

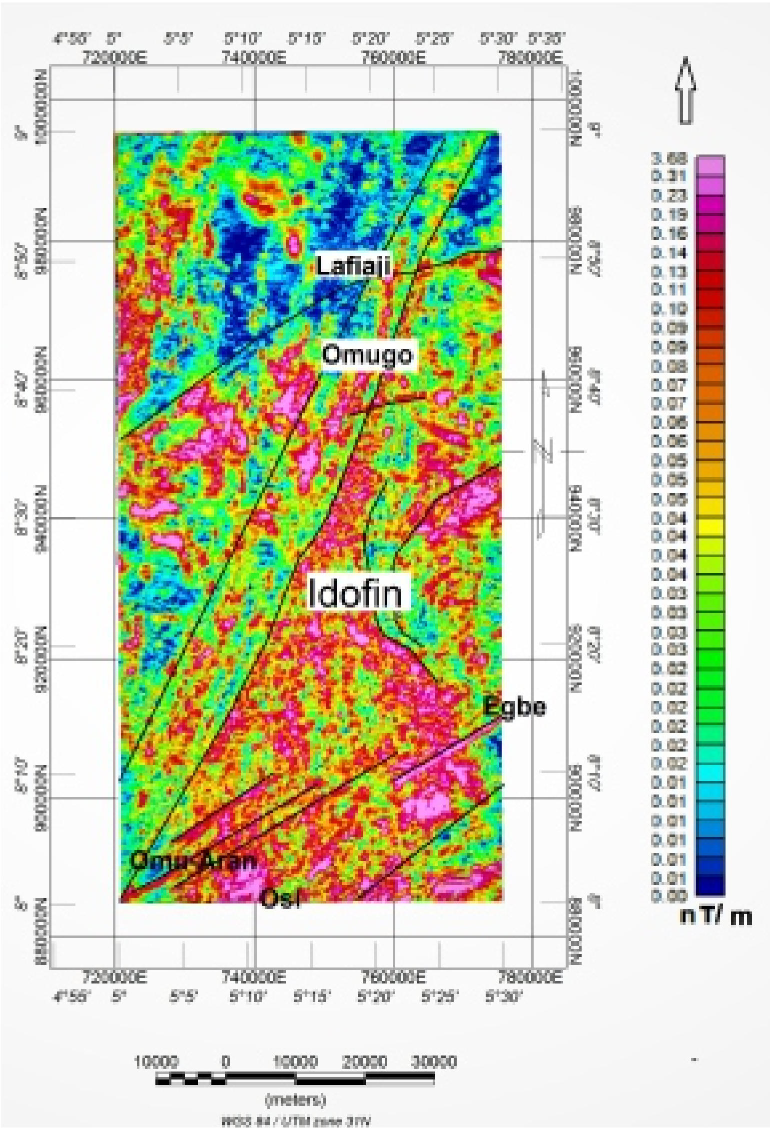


Figure 5: Analytical Signal Amplitude (ASA) highlighting the main magnetic source and lithologies.

Lineament Extraction/Directional Analysis/ Filtering

The shear foliations north of Idofin (Figures 3 and 7(i)) are represented by LS foliations. The S plane trends NW-SE, represented by linear high magnetic intensity corresponding to negative elevation while the S planes are represented by S-type foliation fabric indicating a sinistral sense of movement, at variance with the adjacent Ifewara-Zungeru dextral shear sense. A set of reverse L shear bands occur to the west of the S and L shear foliations. The L bands indicate an overprinting of the earlier L-S, synthetic dipping shear planes by mega thrusts of an antithetic dipping reverse crenulation. These L bands are invariably blind thrusts identified by using high-resolution aeromagnetic data analysis.

Regional intense shortening and transposition of some initial N-S to NNE-SSW trending recumbent/isoclinal (Figure 1c) folds on the eastern limb of the mega fold led to the development of flattened, tight Isoclinal folds and parallel axial plane folds, a common deformational feature in most orogenic belts.

One of the major structures that can be resolved from the geophysical data in this area is characterized by an older ENE-WSW and E-W trend and younger NE-SW trending structures.

The limbs of the NE-SW trending isoclinal mega fold appear as NE-SW trending folded strips and intercept the ENE-WSW lineaments (Figures 3, 4, 5, 6 and 7) around Omu-Aran. Shorter E-W lineaments cut across the NE-SW trending structures. The NNE-SSW lineaments are part of the Ifewara-Zungeru Mega Fault.

Overprinting Relationship and Regional Tectonics

Three areas on the interpreted map elucidate the structural evolution of the study area appropriately. These are the western part of the map that hosts the Ifewara-Zungeru Strike-slip fault zone and the Oreke-Okegbo mega fold; the area around Aran where the NNE-SSW shear zone intersects/cuts across the NE-SW structures; and the southeastern part of the map, around Egbe ductile shear zones and thrust structures are dominant.

The Ifewara-Zungeru strike slip fault zone and the Oreke-Okegbo Mega fold

The mega fold is hosted within a dextral strike-slip fault zone (Figures 1a, 1b and 1c). Movement within the strike-slip fault evinced the translation and rotation of large blocks of crust and influenced the formation of the mega folds within it. This is mostly due to the juxtaposition of horizontal shears on vertical or sub-vertical surfaces (Sylvester 1989). Such intraplate transform faults are common in orogenic belts and serve as a partition between the extension and shortening domain and also expose buried shear zones. The strike-slip fault formation must have been enhanced by multiple reactivations of old fundamental fractures, first during the separation of the South America and African plates, and at other times, through accommodating different episodes of deformation. The presence of faults that cut across other preexisting rocks and structures categorized as early Pan African age suggests late Pan African age.

The Oreke-Okegbo Mega fold can be inferred to have developed from a N-S recumbent fold formed during the D1 ductile deformation phase. The fold is overprinted by a Z fold, to form a Type-2-fold interference around Oreke–Okegbo-Ikosin area (Figure 6). Such refolding might have been caused by a 90° rotation of the maximum compressive force of an initial E-W trending quasi-cylindrical folds (F2) due to a change in tectonic stress orientation, probably during the D2 deformational episode. The present attitude of the fold is also possibly influenced by movement along with the bounding strike-slip fault. On the eastern limb around the Oke-Iyan area, three types of folds are represented (Figure 6). The first fold (F1) is the N-S isoclinal/recumbent fold (similar to Okemesi Fold). This fold was tightened and tilted into an NNE-SSW (S2) axial planar fold during the D2 deformational episode. The NNE-SSW axial plane fold was later refolded to an open fold (F3) with a NW-SE trending axial plane (S3). The latest deformation indicates a horizontal or nearly horizontal open fold on the limb of the D1 to D3 folds (represented by S4 (Figure 6)).

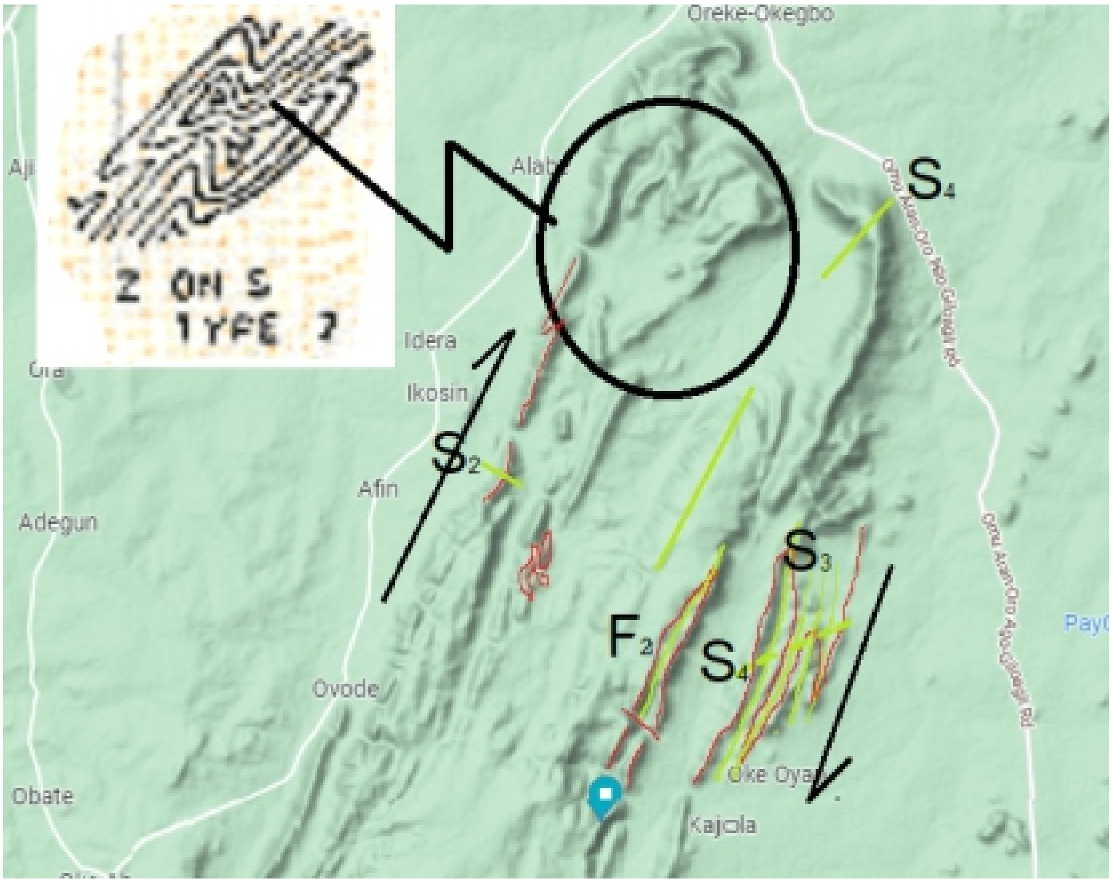


Figure 6: Interpretation of some of the timing and relationship between the folds and fabrics (axial planar foliations) from the Google map image of Oreke-Okegbo area.

The Egbe area

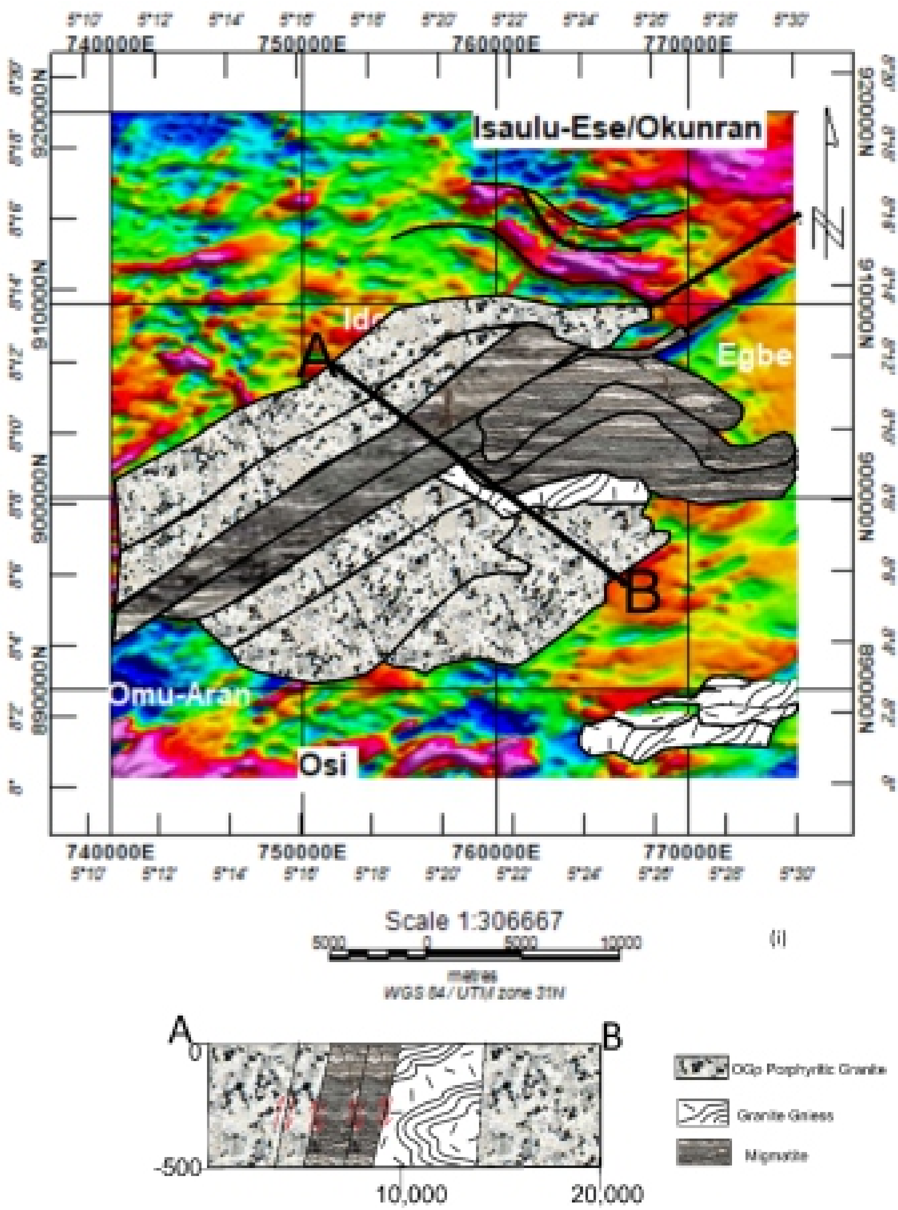
The Egbe folded area (Figures 3 and 7) is dominated by both anticlinal domes formed by the refolding of an earlier east-west trending tight to isoclinal/recumbent fold (F1) to an open anticlinal fold with N-S to NNE-SSW axial plane. This open fold is associated with the D2 deformational episode, and the tightening and refolding of the FI fold must have occurred during the D2 or later deformational episode. This fold is also truncated by a NE-SW trending strike-slip fault at the hinge zone. Cross-cutting of a more prominent NE-SW lineament on NW-SE trending lineaments is also noticed at the peak of the Egbe anticlinorium (Figures 7(i), 7(ii), 7(iii) and 7(iv)). The E-W trend terminates against the NE-SW trend, indicating an older E-W trend of Eburnean (2.2–2.0 Ga), while the N–S, NNE-SSW and NE–SW structural features formed during the Pan-African orogeny event (600 Ma)).

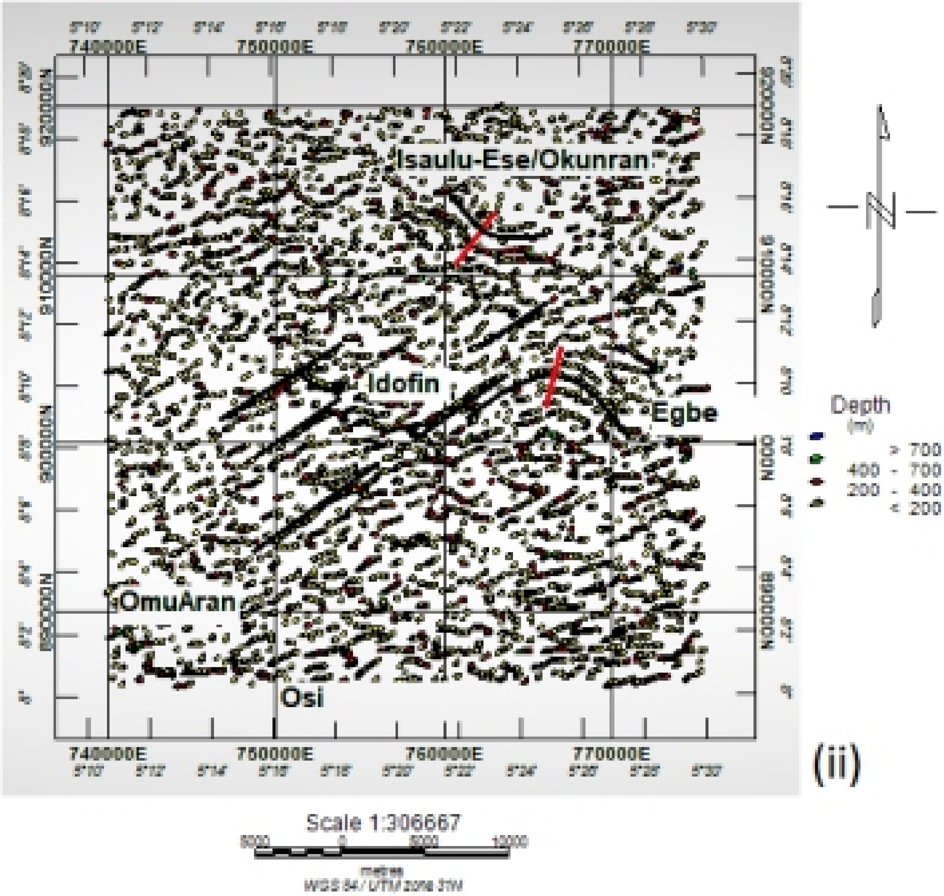
Some thrust structures can be interpreted from the Idofin and Egbe area (Figure 7(i)). Eastward tectonic vergence of Banded gneiss roof thrust units (with lower metamorphic grade than the underlying Migmatite) is observed. The NE-SW thrust duplexes (made up of bands of gneisses and amphibolites, the contact of each band coincides with NE-SW trending faults) are responsible for both shortenings and for slip transfer from the floor thrust and E-W trending decollement upward towards the anticlinorium on the roof thrust. The NE-SW trending, east-dipping thrust faults with anticlines plunging to the SE and the NW are associated with the D4 deformational episode (Okonkwo, 2006).

A shear zone with a sinistral sense of shear occurs around Omugo-Egbe (north of Idofin, Figure 7(i)), consisting of L and S tectonites with stretch lineation in the NW-SE. The NW-SE tectonites are coeval with D3 ductile thrust structures similar to those identified in the Jebba area by Okonkwo (2006).

Another area with pronounced shearing is at the

Northwestern part of the Idofin-Egbe thrust structure (Figures 3 and 7(i)). This shear zone is similar to the Koro-Egbe NW-SE shear zone described by Adedoyin *et al.*, (2019a), with the presence of NW-SE trending sinistrial bands (mostly Band gneiss), L-S fabrics, rotated clasts and an asymmetric fold at Isaulu-Ese/Okunran axis. The following discussion will focus on the interpretation of the aero-radiometric data. Figure 7(iv) offers significant insights into both the lithology and lineaments of the area. The sharp contact (part of the Ifewara-Zungeru fault) represented by NNE-SSW lines on the western part of Figure 7(iv) indicates the boundary between the blackish (low potassium, thorium, and uranium) zone on the RGB ternary map and the bluish zone in the southwestern part, which represents a high uranium zone. In contrast, the northern parts transition to a whitish zone with high levels of potassium, thorium, and uranium. The middle portion of this sharp contact transitions to a red zone (indicating an increase in potassium) and a green zone (indicating an increase in thorium). The different colours on the ternary map closely correspond to different rock types when compared to the geological map. The rock contact on the eastern part is not sharp but rather gradational, marked by linear to curvilinear structures characteristic of sheared and folded (the anticlinorium at Egbe, and the shear zone east of the mega fold) structures as indicated on the lineament map (Figure 7(iv)) and further confirming the interpreted structures from the magnetic data interpretation.

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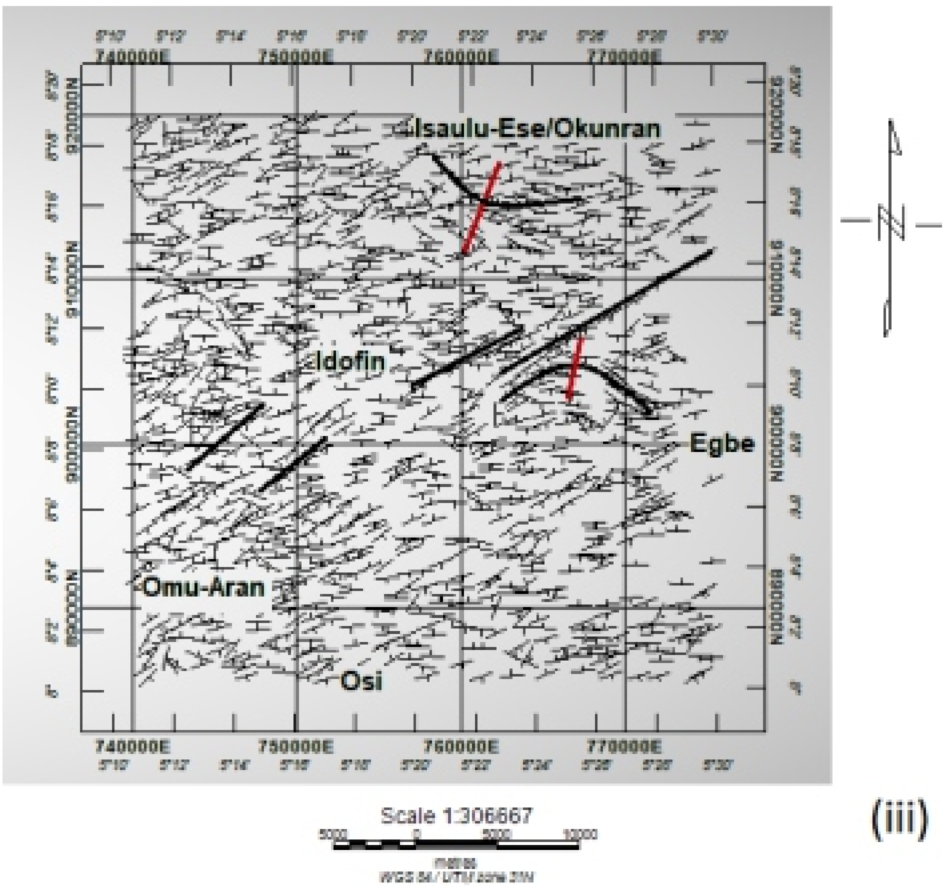
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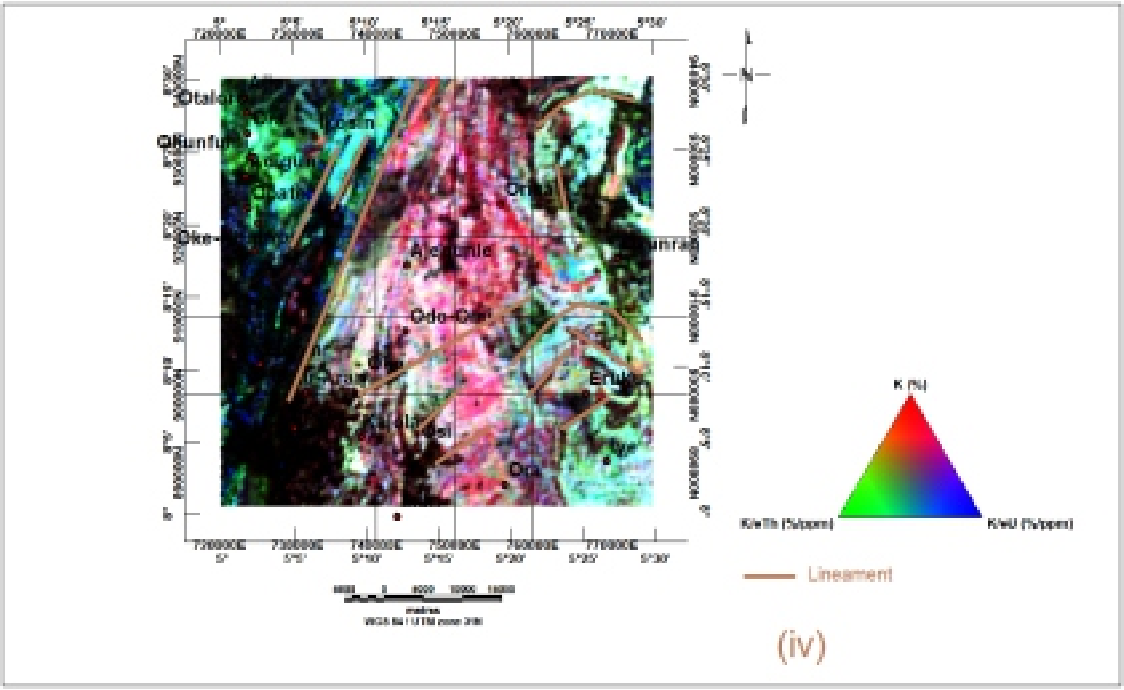

Figure 7: (i) The Egbe anticlinorium together with the lithologic and structural interpretations overlaid on the Colored FVD (ii) the Eular deconvolution map (iii) and the CET map of southeastern parts of the interpreted aeromagnetic map (iv) aeroradiometric data interpretation showing some of the prominent lineaments.

The interpreted area between Omugo and Egbe reveals a mega L and S fabric and ductile shear foliations indicative of progressive high-strain deformation. Other notable structures here include the Isanulu-Ese/Okunran NE facing synclinal folds with NE-SW trending axial plane. The area around Omu-Aran

The NNE-SSE extensional fractures are truncated/crosscut by the NE-SW shortening/thrust faults (Figure 3). This probably suggests a progressive change from the NNE-SSW extension around Omu-Aran area to a NE-SW shortening between Idofin and Egbe. It indicates that the folding and shearing in the eastern section i.e., around the Ifewara-Zungeru shear zone, preceded the extension. The NNE-SSW trans tension affected the Oreke-Okegbo mega fold more from Omu-Aran to Okemesi area.

The southeastern part of the map, from Aran to Egbe is characterized by NE-SW trending lineaments. Some of the major structures that can be resolved from the interpretation of geophysical data include the refolding of the F1 recumbent folds by both NNE-SSW F2 folds and approximately N-S to NW trending F3 folds.

Based on this interpretation, the structures observed must have evolved from at least four deformation events. The first two events are ductile, with the first event producing the F1 recumbent/Isoclinal folds with an axial plane oriented in a general E-W direction. The second folding event resulted in the development of F2 open to tight folds with axial plane varying between N-S to NNE-SSW. The D3 deformation event produced ductile F3 folds, and shear zones, with NNE-SSW to NE-SW trends, as well as a brittle deformation, producing a regional scale brittle strike-slip faults with NE-SW orientation. The D4 is a brittle/ductile deformational episode. The dip-slip faults oriented in a general ENE-WNW direction are considered to have resulted during a D4 event, while the ductile phase is marked by the development of reverse/thrust faults with pinch and swell structures. This period is also marked by evidence of the fourth and youngest deformation event in the area.

Correlation with Regional Tectonics

Fundamental intraplate strike-slip fault zones such as the Ifewara-Zungeru Fault Zone, exposed as large shear zones (Figures 1 and 7) are elements of intracontinental deformation associated with Neoproterozoic Pan-African Brasiliano orogeny. Such intracontinental orogeny could be formed at some distances from the active plate margin. The initiation of orogenies away from plate boundaries could be due to the transmission of plate-boundary stresses and intraplate stresses, with examples in the Tian Shan and Altai (Asia); Alice Springs and Petermann orogens in central Australia (Piazolo *et al.*, 2020). This contradicts one of the fundamental assumptions of plate tectonics which assumes that all major deformation occurs at the plate boundaries and the intraplate motion and deformation are negligible (Van der Pluijm and Marshak 2004; Raimondo *et al.* 2014). However, intraplate orogeny in different parts of the world is usually due to stress perturbation (Silva *et al.*, 2018).

The Ifewara-Zungeru deformation belt most likely takes its source from the oceanic lithosphere. This zone is spectacular with its about 700 km length coverage forming a major weak zone with discontinuity that is possibly involved in transferring displacement from the oceanic lithosphere into the adjacent continental lithosphere. Such zones are susceptible to reworking, reactivation of structures, multiple phase deformation and orogenies represented by successive imprints. Intraplate strike-slip faults are commonly associated with thrusting similar to the Northern and Eastern Tibet region in East Asia as explained by Molnar & Lyon-Caen (1989) and Meyer *et al.* (1998). The Ifewara- Zungeru Zone is associated with both early contractional tectonics and later extensional tectonics. The early contractional tectonics is responsible for the formation of folding, thrusting and shearing within and around this weak zone as well as later extension and elongation of the folds. This is similar to the deformation in the Serido Belt of the Borborema Province, NE Brazil (Archanjo *et al.*, 2002) which is also dominated by NE-SW striking upright to inclined folds (in the western domain) and thrust duplexes in the eastern domain (Patos shear zone). The NNE trending dextral motion Ifewara-Zungeru shear zone with all the coeval upright and inclined fold belt forms the western domain; the adjourning E-W trending zone which is subdivided into thrust stacks by several NE trending imbricate thrust faults and other NE-SW trending sinistral faults (enclosing the highly folded zones)) form the eastern domain around Idofin–Egbe. There is evidence of early dextral motion (Idofin–Egbe thrust section (more than 41 km from Ifewara-Zungeru fault trace in the west) and of late NW-SE sinistral motions around Omugo-Egbe (north of Idofin). The major difference in geometry is that in the Borborema Province the E-W trending shear zone splays off the NE trending zone, however, the NNE trending Ifewara-Zungeru Shear Zone seems to intersect/crosscut the E-W trending Egbe shear zone. The presence of metasediments, gneisses and granites is common to both. The folds, shear structures and thrust duplexes bear imprints of intraplate crustal compression, while the Ifewara-Zungeru dextral strike-slip fault zone is both compressional and extensional.

Mineral and water resources

The late stage of Pan-African deformation has a strong influence on both lithologic and structural control of gold, Tin, Niobium and Tantalite mineralization in pegmatites and along certain quartz-veins (Kolawole *et al.* 2021). Gold and other valuable mineralization have widespread occurrences around this region (Okolom/Isanlu schist belt). Some are already being exploited profitably along an extensive NNE-SSW shear zone. Garba (2003) through geochemical investigation, gave credence to a metamorphosed-hydrothermal fluid source that migrated during the brittle phase of the Pan African Orogeny, through tectonically generated regional discontinuities as the gold mineralization source in Nigeria. Thus, most gold occurrences in Nigeria have a spatial relationship with regional structures, irrespective of the rock type/lithology it's cutting through (Garba, 2000). Target gold prospecting sites within the area have been identified as points where regional NE-SW and NNE-SSW lineaments offset the N-S structures. Gold mineralization occurs within quartz veins that are associated with some of the major fractures. Active mining sites exist in Ndeji environment, with ongoing mining of Tantalite, Columbite and Cassiterite (Aliyu *et al.*, 2020). Identification of the prolific fractures and their magnetic characteristics will help in identifying other potential sites for mineral exploration. Salawu (2021) reported the indisputable correlation between the interpreted structural features and gold mineralized zones within the northern parts of this area and the use of such an association for predicting gold occurrences and other economic mineralization. The Koro-Egbe NW-SE (Figure 3) trending shear zone with asymmetric folds occurs within biotite gneisses, granites, pelitic schists and amphibolite rocks that host beryl, tantalite, columbite and gold (Adedoyin *et al*., 2019b).

Some waterfalls occur within the interpreted area, these include the Owu waterfall at Owa Kajola in Ifedore Area (Latitude 8°20'50.215" and Longitude 5°8'41.647") and the Ero-omola waterfall at Odofin Igbana in Oke-Ero, the Ayikunugba waterfalls located at Ila-Orangun. These waterfalls will be a significant tourist attraction if well-developed and managed.

The Owu waterfall forms a cascade that is about 120 m high (Adedoyin, 2017), one of the highest in West Africa. The waterfall occurs at an outl*et al*ong the Ifewara- Zungeru fault boundary on the Omu-Aran quartzite ridge. The formation of this waterfall might be related to movement along the fault boundary, coupled with the opening and splaying of fractures along the fault boundary (Ponmanee and Kanjanapayont, 2021), as well as the subsidence/negative stepping (flower structure) of the Ifewara-Zungeru strike-slip fault around the area.

DISCUSSION

The interpretation from the aeromagnetic data analysis confirms the subsurface continuity of the surface features within the study area

The broad anticlinorium at Egbe-Idofin (Figures 3 and 7) at the eastern margin of the Egbe fold and is interpreted as a large ramp anticline. This anticlinorium is accompanied by a refolded recumbent fold now forming an upright fold on the eastern limb. The western limb reflects a series of foreland dipping hanging wall ramps formed by NE verging stack units overlying the footwall and floor thrust, which are truncated in places. This conforms with the northeast-directed transport of nappe during D1 as speculated by Caby, 2001. The master NE-SW-directed dextral fractures and the NE verging individual imbricate thrust fault which separates the duplexes (transfers displacement from the floor thrust to the roof thrust) are younger than the earlier formed N-S to NNE-SSW structures. These fractures are foci for possible movement in this area.

The opposite shear sense exhibited by Koro-Egbe shear zone (sinistral), the NE-SW dextral strike-slip faults parallel to the imbricate thrust bands at Idofin and the adjacent Ifewara-Zungeru strike-slip fault (dextral) indicate possible tectonic inversion due to orthogonal modification of the principal stress axes during different deformational episodes. The presence of lozenge structures as well as reverse/thrust faults were used to assess the overall shear sense of the structural regime. With more than half of the structures indicating dextral shear in their current orientation, there are several hypotheses about the formation of double plunging folds. One posit on the possible formation of such folds is that they are formed by equilateral compression (at right angles) along a horizontal line (Ji and Li, 2020). The Oreke- Okegbo (double plunging anticlinal) (dominated by quartzite ridges (Figures 1a, 1b and 1c)) must have formed from the refolding caused by a perpendicular rotation of the maximum compressive force of an initial E-W trending quasi-cylindrical folds due to change in tectonic stress orientation. The Okemesi fold is a large recumbent fold (Caby, 2001). These folds are bounded by strike-slip faults with several shear evidence. The dominant lithology in this fold belt is pelitic schists interbeded with quartzite (schistose, micaceous and bulky in places), banded Iron formation, talc and amphibolites (Annor *et al*., 1997; Olobaniyi, 1997; Adeleye *et al*., 2018).

The above line of reasoning informed the consideration of the refolding, overthrusting and syn metamorphism of earlier formed sediments (possibly during the Kibaran Orogeny) along an E-W direction. The metasomatic fluid, hydrothermal fluid from migmatization and granitic intrusions released during the metamorphism must have escaped into and probably trapped along the weak zones. This must have further enhanced the intense compression that accompanied the refolding and over thrusting during the period. The rate of motion and transfer of such materials along individual imbricate faults that separate the thrust bands must have increased too. Future exploration efforts should be concentrated along the NE-SW imbricate slices as well as the core and nose of the refolded folds close to Idofin-Egbe. It is also obvious that these structures are concealed from the surface by later crustal covers.

CONCLUSIONS

It can be concluded that the results of surface geology and geophysical investigation in the interpreted region suggest the concept of deep-rooted overthrusting.

Aside from the implication for mineralization, the active NE trending master thrust bands and the NE-SW trending strike-slip faults in the Egbe region might also have implications for seismic hazards. More seismic activities should be expected around the Omu-Aran-Ilofa area where the Ifewara-Zungeru Fault Zone intersects/crosscut the NE-trending faults, suggesting that the deformation was non-coaxial but pure shear and the rocks moved progressively from the extensional (in the west) to shortening (in the east), indicating simple shear deformation. These intersection zones are major weak zones. The fractures are capable of enhancing fluid flow, heat flow, and/or stress flow and therefore capable of moving at slight increased (induced or natural tectonic) stress in the area. Such areas are capable of enhanced seismic risk (due to fault rejuvenation) and should be further investigated, though only a single seismic activity has been reported in this area in recent times (Adepelumi, 2021). However, similar structural scenarios were responsible for earthquake events in Zagros Folds Iran as reported by Berberian (1995).

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CONFLICT OF INTEREST

I declare that there is no conflicting interest.

AUTHOR'S CONTRIBUTION

The author conceived the idea, procured the data, analysed and interpreted the data.

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