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Mapping Basement Features and Deep Crustal Structures in the Lower Benue Trough: A 2D Reduction to Pole and Upward Continuation Approach

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ABSTRACT

This study focuses on deep-seated magnetic sources in the southern Benue Trough of southeastern Nigeria, using high-resolution aeromagnetic data collected in 2010 by the Nigerian Geological Survey Agency (NGSA). The dataset was processed through reduction to the equator (RTE), and upward continuation at multiple levels (200 m, 1000 m, 5000 m, 20,000 m, and 50,000 m) to distinguish shallow from deep crustal anomalies. The results highlight a clear division of the region into distinct magnetic domains. At deeper levels, upward continuation to 20 km and 50 km isolates major crustal features. A large south-central magnetic body beneath Uzoakali–Bende–Umuahia emerges as the principal deep-seated source, while the Abakaliki axis and Oban Massif are restricted to upper and mid-crustal depths. The central Benue Trough appears as a regional magnetic low, reflecting thick, non-magnetic sedimentary cover above a deep basement depression. The integrated interpretation defines the deep basement framework, maps intrusive complexes, and constrains structural controls on mineralization. These findings provide valuable insights for both mineral exploration and hydrocarbon basin evaluation in southeastern Nigeria.

1. Introduction

The magnetic method (geomagnetism) is a passive geophysical technique based on the measurement of local variations in the Earth's magnetic field caused by differences in magnetic susceptibility contrast among subsurface rocks and materials. Magnetic susceptibility (k) is the ability of a material to become magnetized when subjected to the Earth's magnetic field. When a buried body possesses a susceptibility that is significantly different from that of its surrounding host rocks, it produces a local perturbation in the ambient geomagnetic field. If a field value obtained shows a contrast from the value of the surrounding magnetic field, such deviation is referred to as a magnetic anomaly [1].

The total magnetic field intensity measured in the field (TMI) is a composite field consisting of several superposing components: the main field generated from the Earth's core, the external field from ionospheric sources, and the anomalous field from crustal sources. For mineral and environmental investigations, the anomalous field is of primary interest, and it can be further separated into two components - regional anomalies and residual anomalies [2].

The regional anomaly component is characterized by low frequency, long wavelength and broad spatial extent. It originates from deep-seated, large-scale geological structures such as deep basement topography, major intrusive complexes and crustal boundaries. It therefore provides information about anomalous sources at great depths. While the residual anomaly component is characterized by high frequency, short wavelength and localized closures. It is superposed on the regional field and originates from

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shallow, near-surface sources such as ferruginous sandstones, ironstone cappings, buried metallic objects, weathered zones and subsurface voids. In soil piping studies, negative residual anomalies often delineate zones of leached sands, water-saturated pipes and air-filled voids where magnetic mineral susceptibility has been reduced or completely removed by internal erosion, while positive residual anomalies indicate preserved iron-rich lateritic caps.

Several methods exist for regional-residual separation, including graphical methods, moving average, polynomial fitting, wavelength filtering, and upward continuation. Among these, upward continuation is the most widely adopted because it is physically-based and stable. It has been successfully applied in previous studies such as [3], [4], [5], [6], where it was used to enhance deep sources and suppress shallow noise, thereby allowing more accurate interpretation of magnetic anomalies.

In this method, the observed magnetic field measured at the surface is mathematically recalculated to a higher elevation. As continuation height increases, short-wavelength (shallow) anomalies are progressively attenuated, while long-wavelength (deep) regional anomalies persist. The residual anomaly is then obtained by subtracting the upward-continued (regional) field from the original field.

In this research, 2D upward continuation was performed at multiple heights of 200 m, 1000 m, 5000 m, 20000 m and 50000 m to separate shallow and deep magnetic anomalies and to ensure continuity in the aeromagnetic mapping of the Lower Benue Trough.

1.1 Study Area

The Benue Trough Figure (1) is divided into Lower, Middle, and Upper segments based on major depocenters near towns rather than sharp geological boundaries. In the Lower Benue Trough, sedimentation began with the marine Neocomian–Albian Asu River Group, and composed mainly of shales with subordinate sandstones, siltstones, limestones, and volcanic rocks such as the Abakaliki Formation and Mfamosing Limestone. These sediments were deposited over Precambrian to Lower Paleozoic basement and represent the first transgressive cycle, largely derived from weathered basement rocks invaded by alkaline basalts before the fast marine flooding of the Middle Albian [7].

Above the Asu River Group, the Cenomanian–Turonian Nkalagu Formation (black shales, limestones, siltstones) is followed by the regressive Agala and Agbani sandstones of the Cross River Group. In the Calabar Flank, the Odukpani Formation (sandstones, limestones, shales) was deposited unconformably on basement during the Late Albian (Ofoegbu and Onuooha, 1989). The Santonian saw non deposition, folding, faulting, uplift, and erosion, pushing the main depositional axis westward to form the Anambra Basin in the Lower Benue Trough [8].

In the Anambra Basin, Early Campanian–Early Maastrichtian deposition of the Enugu and Nkporo Formations (dark shales/mudstones with sandy shales, thin sandstones, and shelly limestones) records the third transgressive cycle; these laterally grade into the sandstones of the Owelli and Afikpo Formations. The Mamu Formation (sandstones, shales, siltstones, mudstones, coals) reflects deltaic facies, laterally interfacing with the marginal marine Ajali and Nsukka sandstones.

In the Paleocene, marine shales of the Imo and Nsukka Formations mark a new transgressive phase, overlain in the Eocene by the tidal Nanka Sandstone, indicating regression [9]. The Oligocene–Miocene Ogwashi–Asaba Formation (sandstones, shales, lignite) belongs to the proto Niger Delta sequences that extend from Eocene to present. Down dip into the Niger Delta, the Akata Shale and Agbada Formation represent Paleocene age equivalents of Anambra Basin deposits and form key elements of the regional petroleum system [10], [11], [12], [13].

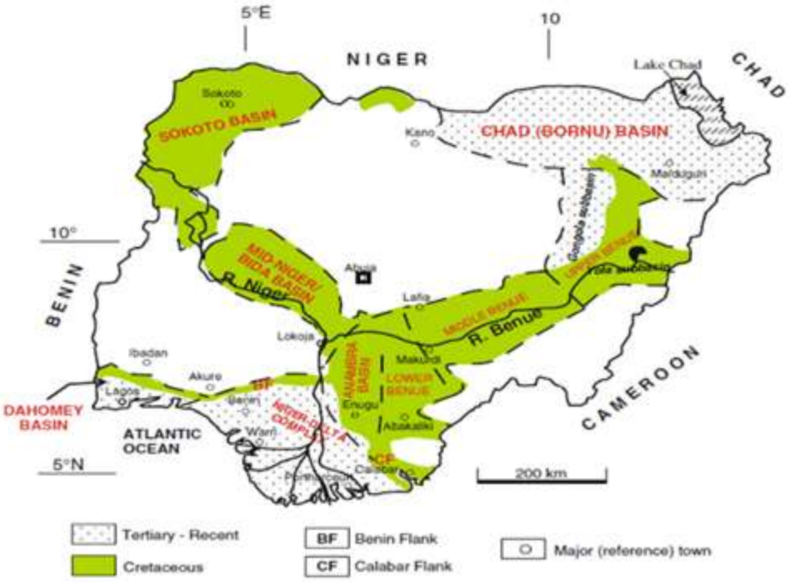


Fig 1. Geology of the Study Area [14]

2. Materials and Methods

2.1 Data Source and Gridding

High-resolution aeromagnetic data for this study were obtained from the Nigeria Geological Survey Agency (NGSA). The survey was conducted in 2010 by Fugro Airborne Surveys, Netherlands, on behalf of NGSA. The dataset consists of twelve aeromagnetic sheets covering Nsukka, Igumale, Ejekwe, Ogoja, Udi, Nkalagu, Abakaliki, Bansha, Okigwe, Afikpo, Ugep, and Ikom. These sheets were merged into a single composite grid using Oasis Montaj software.

A bi-directional gridding algorithm [15] was applied to generate the Total Magnetic Intensity (TMI) grid at a cell size of 125 m × 125 m. All subsequent maps and filters were derived from this grid.

2.2 Reduction to the Equator (RTE)

At low magnetic latitudes such as southern Nigeria, Reduction to the Pole (RTP) is unstable. To address this, Reduction to the Equator (RTE) was employed. RTE transforms magnetic anomalies into the form they would appear at the magnetic equator, removing asymmetry caused by inclination and centering anomalies over their sources.

The Fourier transform of the observed field is denoted $A_o(u, v)$, while the transform of the vertical magnetization field (RTP field) is $A_p(u, v)$. In the wavenumber domain, the RTP operator is expressed as in equation 1:

$$A_p(u, v) = \frac{A_o(u, v)}{I\cos\theta + D\sin\theta} \tag{1}$$

where $I$and $D$are the inclination and declination of the Earth's main field, respectively, and $A_p(u, v)$. are wavenumbers in the (x, y)directions. Here, $\theta = \arctan(v/u)$and $i = \sqrt{-1}$is the imaginary unit.

For horizontal magnetization ($I \approx 0$) and when $\theta \to D$, the denominator approaches zero, making RTP unstable at the equator. To overcome this, a stabilized RTE formulation was used, incorporating amplitude correction terms to ensure numerical stability.

The relationship between the observed field and the stabilized RTE field is given in equation 2 as:

$$A_{RTE}(u, v) = A_p(u, v) \cdot \frac{[\sin(I) + i\cos(I)\cos(D - \theta)]^2}{\cdots} \tag{2}$$

where $I$is inclination, $D$is declination, $l = \cos I \cos D$, $m = \cos I \sin D$, and $n = \sin I$. Unlike conventional RTE, this special formulation stably transforms the vertical RTP field into the field observable near the geomagnetic equator, preserving anomaly geometry and improving interpretability at low latitudes.

2.3 Upward Continuation

Upward continuation is a potential field transformation that projects magnetic data from the observation plane to higher elevations. Based on Laplace's equation and Green's theorem, it is uniquely defined when the field is fully known at the lower surface.

In practice, upward continuation functions as a low-pass filter. It attenuates short-wavelength anomalies from shallow sources such as dykes and ferruginous bodies, while enhancing long-wavelength anomalies associated with deeper basement structures. This makes it particularly effective for isolating regional fields and mapping deep crustal features.

Mathematically, the upward-continued field is expressed [2] as in equation 3:

$$T(x, y, -h) = \frac{h}{2\pi} \iint \frac{T(x', y', 0)}{[(x - x')^2 + (y - y')^2 + h^2]^{3/2}} dx'dy' \tag{3}$$

where $T(x', y', 0)$is the known total field at the observation surface, and $T(x, y, -h)$is the field at height $h$above the surface. In the wavenumber domain, the operator $e^{-h\sqrt{u^2+v^2}}$exponentially suppresses shallow sources while preserving deep ones.

In this study, upward continuation was applied at 200 m, 1000 m, 5000 m, 20,000 m, and 50,000 m to progressively isolate deep basement structures and assess the depth persistence of major intrusive bodies beneath the Lower Benue in 2D.

5. Results and Discussion

Total Magnetic Intensity (TMI) Anomaly Domains

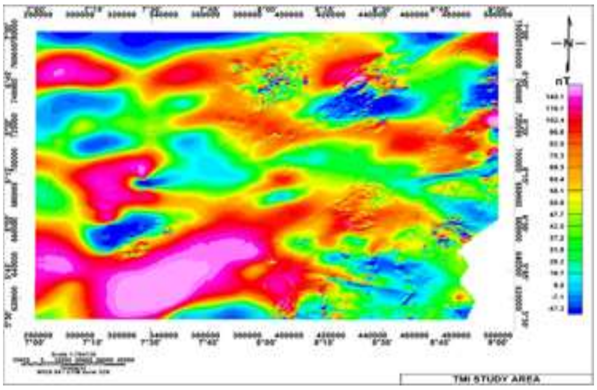
The TMI anomaly map reveals distinct structural domains across southeastern Nigeria, including deep basement uplifts, shallow igneous intrusions, and sedimentary basins. A major magnetic high between Uzoakali, Bende, Ohafia, Oga Ubi, Okigwi, and Umuahia is interpreted as a deep magnetic basement swell or mafic intrusive complex, while localized highs around Afikpo, Bende, Umuahia, and Nsukka indicate shallow mafic intrusions, dolerite sills, or iron-rich horizons.

In the northeast, magnetic highs around Oju, Ogoja, and Ekpatakabo suggest shallow mafic bodies and uplifted basement blocks. The elongated NE–SW magnetic belt along Obokum, Abantoken, Efferaya, and Mkpout Akpankpang marks the structural boundary of the Oban Massif and is associated with dyke intrusions. A similar NE–SW magnetic corridor across Abakaliki, Nkalagu, Agala, and Ikom reflects the folded, faulted, and intruded rocks of the Abakaliki Anticlinorium.

The northwestern magnetic low around Awka, Ozalla, Enugu, and Ndiaboh corresponds to the thick, weakly magnetic sediments of the Anambra Basin, with isolated highs indicating concealed intrusions. Another broad east–west magnetic low along the River Dioko–Iduko–Ubagu Usoanyim axis marks the deepest part of the Benue Depression, characterized by downwarped basement, non-magnetic sedimentary infill, and localized igneous plugs.

Reduction-to-Equator

The RTE-filtered magnetic map removes dipolar shifts, allowing more direct interpretation of subsurface structures and lithology. A broad magnetic high from Uzoakali through Bende, Ohafia, and Afikpo reflects shallow, strongly magnetic igneous bodies associated with Cretaceous volcanic rocks and dolerite sills. Additional isolated highs around Ogoja, Obudu, Nko, and Nsukka–Obolo are attributed to basement uplifts, mafic intrusions, Oban Massif and Obudu Plateau rocks, or ironstone-bearing formations. Broad magnetic lows define major sedimentary basins and structural depressions. The east–west low extending from Igumale through Oju to Iduko marks the central axis of the Benue Trough and its thick non-magnetic sedimentary infill, while the Enugu–Ozalla low outlines the deep Anambra Basin. The map also identifies NE–SW lineaments associated with the Abakaliki Anticlinorium and NW–SE structural breaks interpreted as transfer faults near Ugep–Nko. Symmetrical magnetic lows flanking the Afikpo high confirm its induced nature and its close relationship to the causative subsurface body.



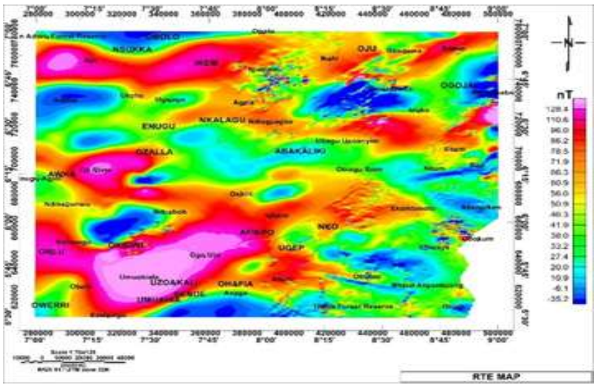


Fig 2. Total Magnetic Intensity Map

Fig 3. Reduction to Pole Map

5.0 Discussion on Upward Continuation

Reduced-to-Equator Upward Continuation (200 m)

The Reduced-to-Equator Upward-Continuation 200 m map (Figure 4) illustrates the total magnetic intensity distribution across southeastern Nigeria following two processing procedures. The first involved reduction to the equator, which helps position magnetic anomalies closer to their causative sources and minimizes the asymmetry associated with the region's low magnetic latitude. The second involved upward continuation to 200 m. This process functions as a low-pass filter by reducing short-wavelength anomalies associated with shallow sources while emphasizing long-wavelength responses generated by deeper or more extensive magnetic bodies. Magnetic intensity values on the map range from approximately −31.6 nT, represented by dark blue, to 126.4 nT, shown in magenta.

A broad magnetic high, represented by red to magenta colours, occupies the northeastern part of the map, extending from Ogoja through Oju to Ikom. This feature corresponds to the regional magnetic expression of the Abakaliki Anticlinorium within the Benue region. In contrast, the central area extending from Abakaliki through Afikpo to Ugep is characterized by a broad magnetic low, represented by blue and green colours. This low is associated with the thick, weakly magnetic sedimentary sequence of the Abakaliki Shales and related formations. The 200 m upward continuation suppresses the influence of shallow dykes and provides a clearer indication of basement depth, suggesting that magnetic sources in this area are either absent or deeply buried. The transition between the central magnetic low and the northeastern high is gradual, trends in a northeast–southwest direction, and probably marks the regional flank of the anticlinorium.

In the southeastern part of the map, around Obokum, Mkpof Akpamkpang, and the Ubia Forest Reserve, a broad magnetic high expressed in orange to red is observed. This anomaly represents the regional magnetic signature of the crystalline basement rocks of the Oban Massif. The western and southwestern parts of the map, including Enugu, Awka, Ozalla, Orlu, and Owerri, are dominated by broad, low-amplitude magnetic responses shown in green and blue. These responses are consistent with the thick sedimentary succession of the Anambra Basin and the northern Niger Delta Basin.

Despite the smoothing effect of the 200 m upward continuation, two distinct circular to sub-circular magnetic highs remain visible around Ozalla and Okigwi. Their persistence indicates that they are likely associated with relatively large, deep-seated intrusive bodies rather than thin, shallow geological features. Their occurrence within a predominantly non-magnetic sedimentary setting makes them important regional targets. Their geometry further suggests the presence of vertical, pipe-like intrusions, possibly of mafic to ultramafic composition [16].

A prominent magnetic high which also displayed in magenta and pink, occurs in the south-central part of the map around Uzoakali, Bende, and Umuahia. With an amplitude exceeding 120 nT, it represents the strongest magnetic feature on the map. Its broad wavelength and persistence after upward continuation indicate a deep and extensive magnetic source beneath the sedimentary cover. Although the feature is not clearly expressed on the derivative maps, it may represent a regional basement uplift or a large buried intrusive body. Such a structure could have influenced the tectonic and thermal evolution of the southern Benue Trough and the northern Niger Delta.

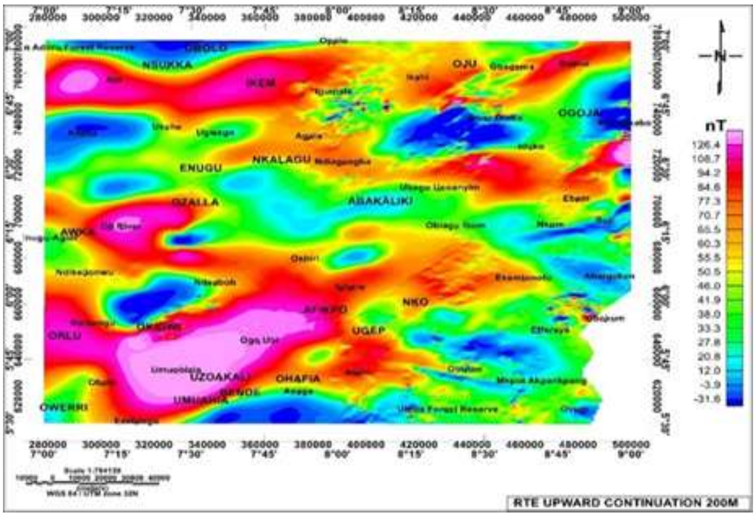


Fig 4. Reduced-to-Equator Upward Continuation at 200 m

RTE Upward Continuation 500m Map

The Reduced-to-Equator Upward-Continuation 500 m map (Figure 5) presents the total magnetic intensity distribution across southeastern Nigeria after reduction to the magnetic equator and upward continuation to an elevation of 500 m. Compared with the 200 m continuation, the greater continuation height applies a more effective low-pass filter, attenuating short-wavelength anomalies associated with shallow magnetic sources while enhancing the expression of broad, deep-seated magnetic bodies. The mapped magnetic intensity values range from approximately −27.9 nT, represented by dark blue, to 123.8 nT, represented by magenta.

The increased continuation height produces a smoother regional magnetic field in which the effects of near-surface dykes, minor structural discontinuities, and cultural noise are substantially reduced. Consequently, the map provides a clearer representation of the magnetic responses associated with deep crustal structures, basement relief, and extensive intrusive complexes.

A broad regional magnetic high, expressed in red to magenta colours, persists in the northeastern sector between Ogoja, Oju, and Ikom. Relative to the 200 m continuation, this anomaly is broader and more diffuse, indicating that its causative body extends to considerable depth. The feature is interpreted as the deeper root of the Abakaliki Anticlinorium and suggests that the shallow intrusive bodies identified in the derivative maps are underlain by a regionally extensive magmatic complex within the Benue Trough. The persistence of its northeast–southwest orientation further indicates that the associated rift-related magmatism constitutes a deep-seated crustal feature.

The central zone, extending from Abakaliki through Afikpo to Ugep, is characterized by a broad magnetic low represented by blue and green shades. At 500 m continuation, the shallow intrusive features evident at 200 m are further attenuated, revealing a more continuous and extensive low-magnetic domain. This feature is interpreted as reflecting the thick sedimentary succession of the Abakaliki Shales and associated formations, which overlies a magnetic basement that is either deeply buried or locally absent. The regional magnetic gradient from the northeastern high toward the central low defines the southwestern flank of the Abakaliki magmatic axis and indicates a fundamental variation in basement composition or depth.

In the southeastern sector, extending from Obokum through Mkpof Akpamkpang to the Ubia Forest Reserve, the broad magnetic high associated with the Oban Massif remains evident in orange and red colours. The slight broadening of the anomaly relative to the 200 m map supports its interpretation as the signature of a large, deeply rooted crystalline basement block. The relatively sharp transition between this high and the central magnetic low to the west continues to indicate a major basin-bounding fault system, although the contact appears more gradual because of the stronger smoothing effect at 500 m continuation.

The western and southwestern sectors, including Enugu, Awka, Ozalla, Orlu, and Owerri, are dominated by a broad regional magnetic low. This pattern is consistent with the thick sedimentary fill of the Anambra Basin and the northern Niger Delta Basin. The circular magnetic anomalies previously identified around Ozalla and Okigwi remain detectable as moderate-amplitude highs, although their boundaries are less distinct at the greater continuation height. Their persistence indicates that they are unlikely to represent thin, near-surface features and instead may be associated with bodies of considerable vertical extent. These anomalies are interpreted as deep-rooted, pipe-like mafic intrusions that penetrate the sedimentary cover and extend into the deeper crust.

The most significant magnetic feature is the extensive high centred around Uzoakali, Bende, and Umuahia in the south-central part of the study area. The anomaly exceeds 120 nT and has a wavelength of several tens of kilometres, indicating a broad and deeply seated source. Although upward continuation generally smooths and reduces the expression of shallow anomalies, the continued prominence of this feature at 500 m suggests that its source is regionally significant and extends to depth. It may represent a major basement uplift or a large buried intrusive complex beneath the sedimentary cover. The absence of a clear expression on the shallow derivative maps further supports its interpretation as a deep crustal feature and an important component of the regional crustal architecture beneath the northern Niger Delta.

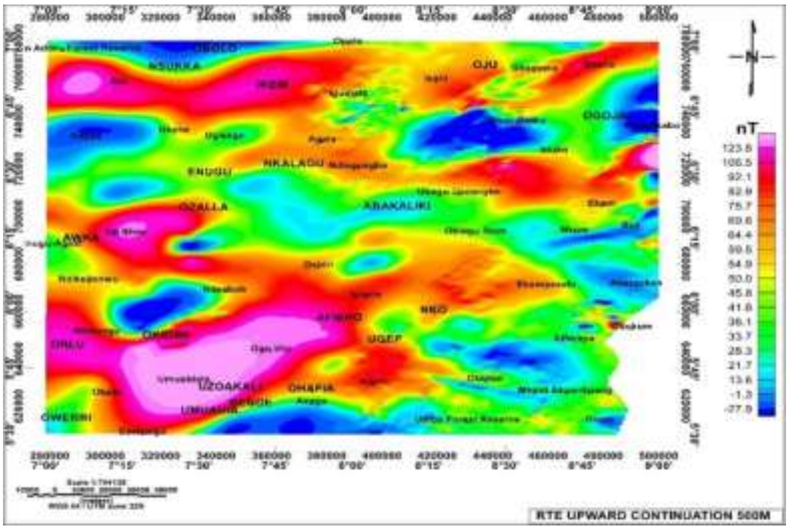


Fig 5. Reduced-to-Equator Upward Continuation 500 m

RTE Upward Continuation 1000m Map

The Reduced-to-Equator Upward-Continuation 1000 m map (Figure 6) displays the total magnetic intensity distribution across southeastern Nigeria following upward continuation of the magnetic field to 1000 m. This processing applies a strong low-pass filter that substantially attenuates short- and intermediate-wavelength anomalies associated with shallow- and intermediate-depth sources, thereby emphasizing broad regional responses generated by deep crustal structures. The data were also reduced to the magnetic equator, which shifts the anomalies more closely toward the locations of their causative bodies. The magnetic intensity values range from approximately −22.2 nT, represented by dark blue, to 120.1 nT, represented by magenta.

Compared with the 200 m upward-continuation map, the 1000 m map exhibits a considerably smoother magnetic field. The effects of near-surface dykes, minor faults, and small intrusive bodies have been substantially attenuated, leaving the responses of the largest and deepest magnetic sources. This level of processing therefore facilitates the interpretation of the regional basement configuration and crustal-scale tectonic features.

The most prominent feature is the broad, high-amplitude magnetic anomaly occupying the south-central part of the map and extending from Uzoakali through Bende, Umuahia, Ohafia, and Oga Ubi. The anomaly has peak values exceeding 100 nT and is broader and more diffuse than its expression on the 200 m continuation map, suggesting that it is generated by an extensive, deeply buried magnetic source. Its persistence at an upward-continuation height of 1000 m may indicate a regional basement uplift, a large concealed intrusive complex, or a zone of enhanced deep-crustal magnetization. The feature dominates the southern Benue Trough and the northern Niger Delta margin and may have exerted considerable influence on the thermal and structural evolution of the region [17].

The northeastern sector, extending from Ogoja through Oju to Ikom, continues to exhibit a regional magnetic high expressed mainly by red and orange colours. However, the anomaly is broader and lower in amplitude than on the 200 m map. It is interpreted as the deep magnetic expression of the Abakaliki Anticlinorium. The pronounced smoothing at 1000 m indicates that the numerous shallow intrusions identified on the derivative maps are underlain by a coherent, deep-seated magnetic basement along the Benue Trough axis. The persistence of the northeast–southwest elongation further suggests that the rift-related structural fabric extends into the deeper crust.

The central region around Abakaliki, Nkalagu, Afikpo, and Ugep is characterized by a broad magnetic low represented by blue and green shades. At the 1000 m continuation level, most shallow magnetic effects have been attenuated, leaving the regional signature of a thick, weakly magnetic sedimentary cover overlying a deeply buried basement. The transition from this low toward the northeastern and southeastern magnetic highs defines the regional geometry of the basin. The central low may therefore represent an area of considerable sedimentary thickness and a relatively deep basement surface [18].

In the southeastern sector, the Oban Massif, extending around Obokum, Mkpof Akpamkpang, and the Ubia Forest Reserve, appears as a broad magnetic high expressed in orange and red. The detailed anomalies visible on the derivative maps are no longer resolved, leaving only the integrated magnetic response of the crystalline basement. The western margin of this high forms a pronounced regional gradient, marking the fault-controlled boundary between the basement massif and the sedimentary basin to the west.

The western and southwestern sectors, encompassing Enugu, Awka, Ozalla, Orlu, and Owerri, are dominated by broad magnetic lows associated with the Anambra Basin and the Niger Delta Basin. These lows are consistent with the presence of thick sedimentary successions and the absence, or considerable depth, of strongly magnetic basement rocks. The circular anomalies near Ozalla and Okigwi, which were distinct on the 200 m continuation map, are considerably attenuated at 1000 m. Their reduced amplitudes suggest that they have limited vertical extent and are predominantly upper-crustal features. Nevertheless, the persistence of a weak central high at Okigwi may indicate a deeper root than that associated with the Ozalla anomaly.

A separate, isolated magnetic high persists in the northwestern part of the map near Abi, north of Nsukka. Its survival after 1000 m upward continuation indicates a deep-seated, regional-scale magnetic source. Because it is spatially distinct from the shallow intrusive features associated with the Benue Trough, the anomaly may represent an intra-basement magnetic body beneath the Anambra Basin.

The regional northeast–southwest structural grain of the Benue Trough remains evident in the alignment of the principal magnetic highs and lows. This persistence confirms that the major rift-related structural architecture extends to deep crustal levels. In contrast, the northwest–southeast cross-trends are only weakly expressed at this continuation height, suggesting that the transfer faults identified on the derivative maps are predominantly shallow- to intermediate-crustal structures.

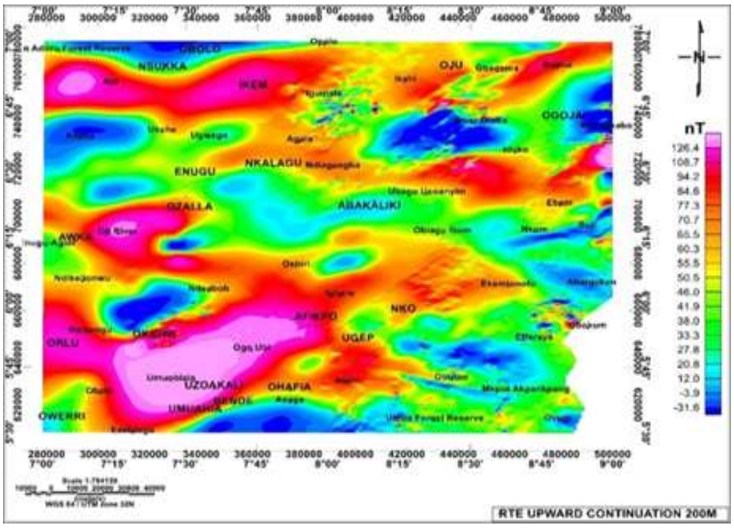


Fig 6. Reduced-to-Equator Upward Continuation 1000 m

RTE Upward Continuation 5000m Map

The RTE Upward-Continuation 5000 m map Figure 7 presents the total magnetic intensity distribution over southeastern Nigeria following reduction to the magnetic equator and upward continuation to an elevation of 5000 m. At this continuation height, the magnetic field is subjected to a strong low-pass filtering effect that substantially attenuates short-wavelength anomalies associated with shallow sources and preserves the broad regional responses generated by deep crustal structures, consistent with the observations of [19]. The magnetic intensity values range from approximately 3.8 nT, represented by dark blue, to 100.2 nT, represented by magenta. Compared with the 200 m continuation and the derivative maps, the field is considerably smoother.

The 5000 m upward continuation largely suppresses the magnetic signatures of near-surface dykes, sills, and thin intrusive bodies that dominate the first vertical derivative, second vertical derivative, and horizontal derivative maps. The remaining magnetic pattern primarily reflects the regional basement configuration and deep crustal architecture. The map is characterized by broad magnetic highs and lows separated by gradual gradients, suggesting that the causative sources are deeply seated, laterally extensive, and possibly located within the middle to lower crust.

A prominent regional magnetic high, represented by red to magenta colours, occupies the south-central portion of the map. It is centred around Uzoakali and Bende, extends toward Umuahia, and continues in the direction of Afikpo and Oga Ubi. With values exceeding 90 nT, this feature constitutes the most pronounced anomaly on the map. Its persistence at a continuation height of 5000 m indicates that it is associated with a substantial deep-seated magnetic source. The anomaly may represent a major basement uplift or an extensive intrusive complex beneath the sedimentary cover of the southern Benue Trough and northern Niger Delta. Its considerable width and amplitude suggest the presence of a significant crustal block that may have influenced the tectonic development and thermal evolution of the basin.

In the northeastern sector, around Ogoja, Oju, and Ikom, a broad magnetic high expressed in orange and red remains identifiable, although it is considerably weaker than on the 200 m continuation map. This attenuation indicates that much of the magnetic response associated with the Abakaliki Anticlinorium originates from shallow- to intermediate-crustal sources. At 5000 m continuation, only the deeper component of the associated magmatic system remains evident. The persistence of the northeast–southwest orientation of the residual anomaly continues to reflect the regional rift-related structural fabric of the Benue Trough.

The central corridor extending from Abakaliki through Nkalagu to Ugep is marked by a broad magnetic low represented by blue and green colours. Its low amplitude and extensive wavelength at 5000 m continuation indicate that the central Benue Trough is underlain either by thick, weakly magnetic sedimentary successions or by basement rocks with low magnetic susceptibility. This zone separates the northeastern and south-central magnetic highs and defines a broad regional crustal depression.

In the southeastern region around Obokum, Mkpof Akpamkpang, and the Ubia Forest Reserve, the Oban Massif remains identifiable as a broad magnetic high expressed in yellow to orange. Its reduced amplitude relative to the 200 m map suggests that, although the massif possesses a deep magnetic component, a substantial proportion of its magnetic response is generated within the upper crust. The boundary between the Oban Massif high and the central magnetic low marks the regional western margin of the crystalline basement.

Across the western part of the study area, extending from Nsukka and Enugu through Awka, Orlu, and Owerri, the magnetic field is generally characterized by low to moderate values. This pattern is consistent with the presence of thick sedimentary successions belonging to the Anambra Basin and the Niger Delta Basin. The circular anomalies around Ozalla and Okigwi, which were prominent on the derivative maps and remained visible at 200 m continuation, are either absent or represented only by weak magnetic inflections at 5000 m. Their disappearance at this continuation height indicates that they lack substantial deep roots and are probably confined largely to the upper crust.

The regional northeast–southwest structural trend of the Benue Trough remains evident in the alignment of the principal magnetic highs and lows. This persistence indicates that the rift system has a significant deep-crustal expression. In contrast, the northwest–southeast cross-trends are no longer discernible, suggesting that they are predominantly upper-crustal structures associated with transfer faults rather than features extending into the deeper crust.

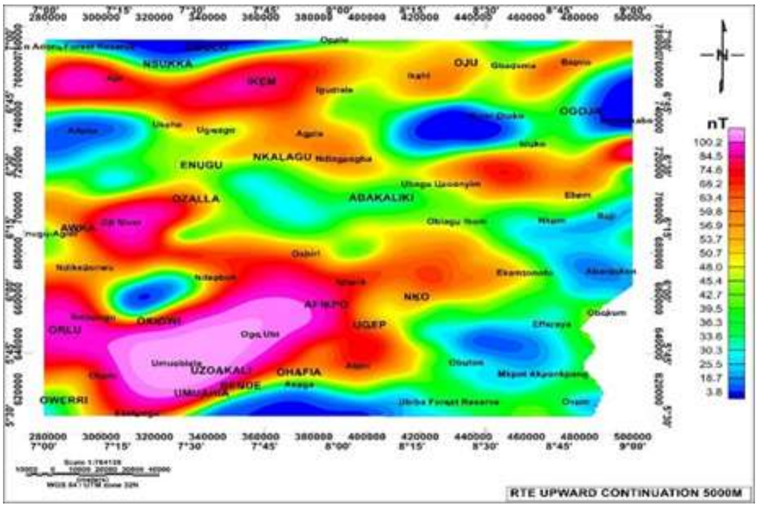


Fig 7. Reduced-to-Equator Upward Continuation 5000 m

RTE Upward Continuation 10000m Map

The Reduced-to-Equator Upward-Continuation 10,000 m map (Figure 8) illustrates the regional magnetic field over southeastern Nigeria after reduction to the magnetic equator and upward continuation to an elevation of 10 km. Continuation to this height applies a very strong low-pass filtering effect, substantially attenuating short-wavelength anomalies associated with shallow and intermediate-depth sources and emphasizing long-wavelength responses generated by deep crustal and possibly upper-mantle magnetic bodies. The magnetic intensity values range from approximately 18.9 nT, represented by dark blue, to 86.8 nT, represented by magenta.

The northeastern sector, extending from Ogoja to Ikom, is characterized by a broad magnetic high expressed in orange and red colours. This regional anomaly is interpreted as the deep-seated magnetic root of the Abakaliki Anticlinorium and the magmatic axis of the Benue Trough. Its persistence after 10 km of upward continuation indicates that the causative magnetic sources are voluminous and extend to considerable depths within the crust. The northeast–southwest elongation of the anomaly further demonstrates that the associated rift-related magmatic system has a regional, crustal-scale expression rather than being restricted to shallow intrusive bodies.

The central region, extending from Abakaliki through Nkalagu to Afikpo and Ugep, displays a broad magnetic low represented by blue and green shades. This feature may reflect the combined influence of thick, weakly magnetic sedimentary successions and a deeply buried or weakly magnetic basement. Its persistence at the 10 km continuation level suggests that the basement beneath this portion of the trough is either relatively non-magnetic or situated at considerable depth. The low therefore delineates the regional axis of the sedimentary basin between the adjacent basement highs.

A major regional magnetic high dominates the south-central and southwestern parts of the map, extending from Uzoakali through Bende, Umuahia, Okigwi, and Owerri. The anomaly reaches peak values above 73 nT and is represented mainly by magenta colours. It constitutes the largest and most intense feature on the 10,000 m map. Its broad wavelength, relatively high amplitude, and persistence after 10 km of upward continuation indicate a large, deeply seated crustal magnetic source. The anomaly may represent a major basement uplift or an extensive mafic intrusive complex beneath the northern Niger Delta Basin and southern Benue Trough. Its size and amplitude suggest that it is a fundamental crustal block with possible implications for the regional tectonic configuration and thermal regime.

A moderate regional magnetic high, expressed in orange, occurs in the southeastern sector around Obokum and Mkpof Akpamkpang. This anomaly corresponds to the deeper crustal expression of the Oban Massif basement complex. Compared with its expression on the 200 m continuation map, the anomaly is broader and has lower amplitude, indicating that the regional basement signature is preserved while the shallow, high-frequency internal fabric of the massif has been substantially attenuated.

The western and northwestern margins around Enugu, Nsukka, and Adaba are characterized by broad magnetic lows represented by blue shades. These lows reflect the regional magnetic response of the Anambra Basin, where thick, weakly magnetic sedimentary deposits overlie a relatively deep basement. The gradients between these low-magnetic zones and the central and southern highs define the regional basement configuration and the principal basin boundaries at crustal scale.

Two notable closed magnetic lows occur east of Ogoja near the River Dioko and southeast of Obokum. At the 10 km continuation level, these circular to oval features are interpreted as deep crustal anomalies. They may be associated with thick sedimentary depocentres or zones of reduced magnetization resulting from metamorphic alteration or thermal effects. Their broad regional expression distinguishes them from the shallow, pipe-like magnetic highs identified on the derivative maps.

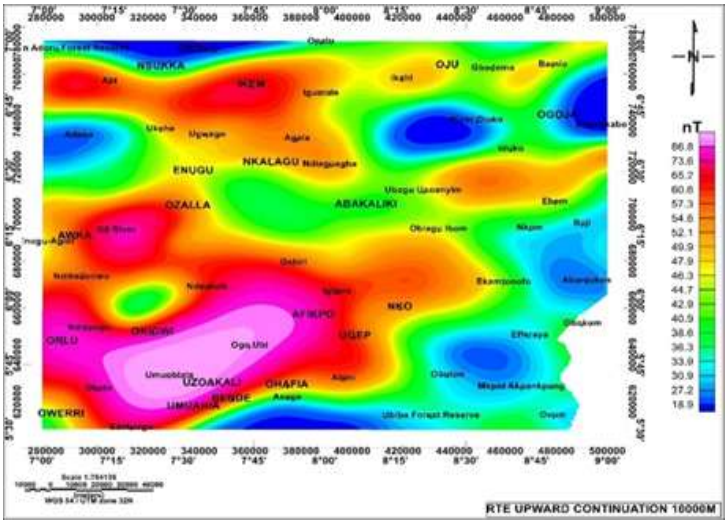


Fig 8. Reduced-to-Equator Upward Continuation 10000 m

RTE Upward-Continuation 20,000 m Map

The RTE Upward-Continuation 20,000 m map (Figure 9) depicts the total magnetic intensity distribution over southeastern Nigeria following reduction to the magnetic equator and upward continuation to an elevation of 20 km. At this continuation height, the strong low-pass filtering effect substantially attenuates short- and intermediate-wavelength components, leaving predominantly long-wavelength anomalies associated with deep, regional crustal sources. Magnetic intensity values range from approximately 31.0 nT, represented by dark blue, to 71.1 nT, represented by magenta. The resulting magnetic field is notably smooth and characterized by broad regional gradients.

The 20 km continuation has greatly reduced the contributions of shallow intrusive bodies, dykes, and upper-crustal faults that were prominent on the derivative maps and on the 200 m to 1000 m continuation maps. The resulting image therefore provides a regional representation of the deep basement configuration and the principal tectonic framework of southeastern Nigeria.

The most prominent feature is a broad, high-amplitude magnetic high occupying the south-central part of the map. It is centred around Uzoakali and Bende, extends through Umuahia, and continues toward Afikpo, Ohafia, and Okigwi. The anomaly exceeds 64 nT and has a wavelength greater than 100 km. Its persistence and regional dominance at 20 km upward continuation indicate that it is associated with a large, deeply seated magnetic source, possibly located within the lower crust or uppermost mantle. The anomaly may represent a major basement uplift, a deep crustal intrusive complex, or a region of enhanced crustal magnetization. It constitutes the most significant deep magnetic domain in southeastern Nigeria and may define a first-order crustal boundary between the Benue Trough and the Niger Delta province.

A broad regional magnetic high, expressed in orange to red, persists in the northeastern sector from Ogoja through Oju to Ikom, although its amplitude is considerably reduced relative to the lower continuation levels. This pattern suggests that the Abakaliki Anticlinorium and the Benue Trough magmatic axis possess a deep crustal component, while much of their total magnetic response originates from shallow- to intermediate-crustal sources. The persistence of the northeast–southwest elongation indicates that the rift-related structural fabric extends into the deeper crust, even though its strongest magnetization is concentrated at shallower levels.

The central portion of the map, extending from Abakaliki through Nkalagu to Ugep and Abini, remains characterized by a broad magnetic low represented by blue and green shades. The considerable width and continuity of this low at 20 km continuation indicate a crustal-scale zone of low magnetic susceptibility or a major regional depression. It corresponds to the deep sedimentary depocentre of the Benue Trough, where the magnetic basement may be deeply buried or composed of inherently weakly magnetic rocks. The low separates the northeastern and south-central magnetic highs and outlines the deeper geometry of the basin.

In the southeastern sector around Obokum and Mkpof Akpamkpang, the Oban Massif is expressed as a broad, moderate-amplitude magnetic high in green to yellow colours. Its substantially reduced amplitude relative to the lower continuation maps suggests that, although the massif has a deep magnetic component, most of its magnetic expression is generated within the upper crust. The gradient between the massif and the central magnetic low to the west marks the regional boundary of the crystalline basement at deep crustal scale.

The western and northwestern sectors, extending from Nsukka through Enugu to Awka and Orlu, are dominated by regional magnetic lows represented by blue and green shades. These features are consistent with the magnetic response of the Anambra Basin and the northern Niger Delta, where thick, weakly magnetic sedimentary sequences overlie a deeply buried basement. The smooth character and low amplitude of the magnetic field indicate the absence of prominent deep magnetic sources within this sector.

Two distinct regional magnetic lows occur as closed contours east of Ogoja near the River Dioko and southeast of Obokum near Oyum. Their persistence and broad spatial extent at the 20 km continuation level suggest that they represent deep crustal features. Possible interpretations include thick sedimentary accumulations, zones of crustal demagnetization, or basement domains with contrasting composition. These lows contrast with the surrounding magnetic highs and contribute to the regional segmentation of the crust.

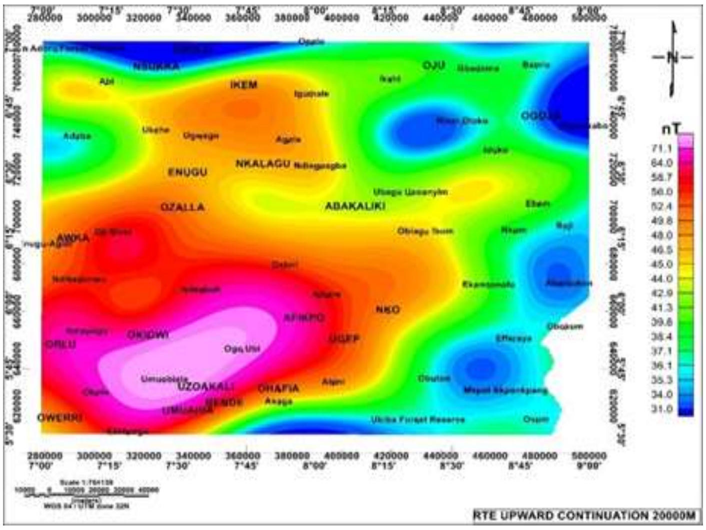


Fig 9. Reduced-to-Equator Upward Continuation at 20000 m

RTE Upward Continuation 50000m Map

The RTE Upward-Continuation 50,000 m map (Figure 10) presents the total magnetic intensity distribution over southeastern Nigeria following reduction to the magnetic equator and upward continuation to an elevation of 50 km. This extreme continuation level produces a very strong low-pass filtering effect, retaining primarily the longest-wavelength components of the magnetic field. Consequently, the map emphasizes broad regional responses associated with deep crustal and possibly upper-mantle sources. The magnetic intensity values range from approximately 33.1 nT, represented by dark blue, to 53.7 nT, represented by magenta. The resulting field is exceptionally smooth and characterized by broad regional gradients.

The magnetic effects of shallow and intermediate-depth geological features, including dykes, sills, faults, and sedimentary-basin structures, have been substantially attenuated. The map therefore provides an image of the first-order crustal configuration and deep lithospheric magnetization of the study area rather than the signatures of individual geological units.

The dominant feature is a broad regional magnetic high centred in the south-central portion of the map around Uzoakali, Bende, Umuahia, and Okigwi. It extends northward toward Afikpo and westward in the direction of Owerri and Orlu. The anomaly reaches peak values exceeding 52 nT and has a wavelength greater than 150 km. Its persistence at a continuation height of 50 km suggests that it is associated with a large, deeply seated magnetic source, potentially located within the lower crust or uppermost mantle. Possible geological interpretations include a major crustal block, a deep mafic intrusive complex, or a region characterized by an anomalously deep Curie-point isotherm. This feature constitutes the most significant deep magnetic domain in southeastern Nigeria and may represent an important tectonic boundary between the Benue Trough system and the Niger Delta province [20], [21].

From the central magnetic high, field intensity decreases gradually outward in all directions. In the northeastern sector, extending from Ogoja through Oju to Ikom, the magnetic field is characterized by green to blue tones, indicating a broad regional low. The magnetic high associated with the Abakaliki Anticlinorium, which was evident on the 200 m to 10,000 m continuation maps, is no longer resolved at 50 km. This attenuation suggests that the magnetic sources associated with the Benue Trough magmatic axis are largely confined to the upper and middle crust and do not possess a substantial deep-crustal or upper-mantle component detectable at this scale.

The central region, extending from Abakaliki through Nkalagu to Ugep and Nko, remains characterized by a broad magnetic low. At the 50 km continuation level, this low merges with the northeastern low to form a continuous zone of reduced magnetization along the principal axis of the Benue Trough. The pattern may indicate crustal materials with low magnetic susceptibility or a basement surface located at considerable depth. It is also consistent with the interpretation of the central Benue Trough as a major sedimentary depocentre associated with crustal thinning.

In the southeastern sector around Obokum, Mkpof Akpamkpang, and the Ubia Forest Reserve, the Oban Massif is no longer expressed as a distinct magnetic high. Instead, the area forms part of the broad regional gradient declining from the south-central anomaly toward the eastern margin of the map. This pattern suggests that the Oban Massif is predominantly an upper- to middle-crustal feature and lacks a significant deep magnetic root that can be resolved at the 50 km continuation level.

The western and northwestern sectors, extending from Nsukka and Enugu toward Awka, are incorporated into the broad magnetic gradient that decreases away from the south-central high. These areas display yellow to orange colours and provide no clear evidence of major deep magnetic sources beneath the Anambra Basin. The pattern supports the interpretation of thick, weakly magnetic sedimentary cover overlying a deeply buried basement with relatively low magnetic susceptibility.

No closed, circular anomalies or localized magnetic features are visible on the map. The smaller highs and lows identified on the 200 m to 5000 m continuation maps, including the anomalies around Ozalla and Okigwi, have been effectively attenuated. Their disappearance at 50 km indicates that they are predominantly upper-crustal bodies without significant deep extensions.

Overall, the 50,000 m continuation map displays a first-order, dipole-like regional magnetic pattern, with a broad high in the south-central region and progressively lower values toward the northeastern and southeastern margins. This configuration reflects deep lithospheric structure rather than the distribution of individual geological formations. The south-central magnetic high may be associated with a thickened mafic lower crust, a zone of mantle upwelling, or a major crustal suture that has concentrated magnetized material.

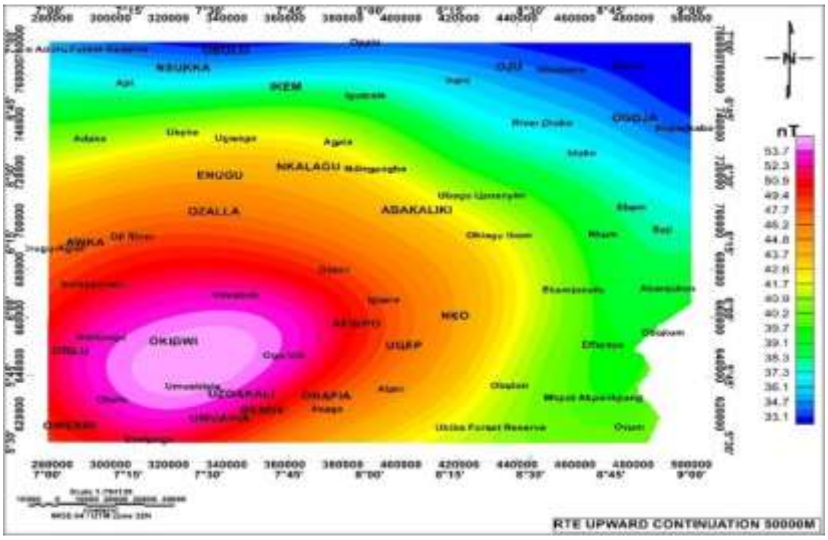


Fig 10. Reduced-to-Equator Upward Continuation 50000 m

6. Conclusions

This study evaluated the regional subsurface framework and deep crustal architecture of southeastern Nigeria using high-resolution aeromagnetic data, Reduction-to-Equator (RTE) filtering, and multi-level 2D upward continuation analysis. By systematically projecting the magnetic field across elevations ranging from 200 m to 50,000 m, the processing isolated long-wavelength regional responses and delineated distinct magnetic domains across the Lower Benue Trough, Anambra Basin, and adjoining basement massifs. The 2D upward continuation identified a major, deeply seated magnetic high centered beneath the Uzoakali–Bende–Umuahia corridor that persists into mid-to-lower crustal levels, representing a fundamental basement swell or deep mafic intrusive complex. Conversely, prominent shallow-to-intermediate intrusive signatures associated with the Abakaliki Anticlinorium and the Oban Massif attenuate at higher continuation levels, confirming their upper-to-middle crustal confinement. Furthermore, a broad, continuous magnetic low along the central axis of the Benue Trough reflects a major regional basement depression filled with thick, non-magnetic sedimentary cover. Overall, these findings establish a refined 2D spatial model of the deep basement configuration, structural lineaments, and regional crustal segmentation in southeastern Nigeria, providing a structural foundation to guide future subsurface geophysical modeling and regional geological investigations.

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