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High-resolution Aeromagnetic and Depth Studies of Parts of the Southern Benue Trough and the Anambra Basin: Implications for Hydrocarbon Prospectivity

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Abstract

High-resolution aeromagnetic studies were carried out in parts of the southern Benue Trough and the Anambra Basin to delineate magnetic features, structures and depths associated with hydrocarbon prospecting within the basins. Nine aeromagnetic sheets covering the study area were used in generating grids and maps used. The Total Magnetic Intensity, Reduction to the Equator, Reduction to the Equator Inverted, First Vertical Derivative, Second Vertical Derivative, Tilt-Derivative and Analytic Signal were used in delineating magnetic sources, their distributions, trends and structures present, while the Source Parameter Imaging gave depth ranges to magnetic sources. Magnetic sources occur more in the southern Benue Trough. Structures delineated include faults, ridges, shear zones, intrusives and volcanic area. These structures trend mostly in the northeast-southwest direction and occur more in the southern Benue Trough. Some of these structures could serve as traps and migration pathways for hydrocarbon, with intrusives serving as source of heat for source rock maturation. Depth vary from below -168.78 to above -2.627.95m. Areas with maximum accumulation of sediments were identified and labelled as target areas 1, 2 and 3. These areas exceed the 1000m thickness required for a potential basin if other petroleum system elements are present. Results from this study shows the northern and southern parts of the study area have better potentials for hydrocarbon prospecting.

Keywords: *High-resolution; Aeromagnetic; Depth; Structures; Hydrocarbon prospectivity.*

1. Introduction

Aeromagnetic studies use the magnetic method to study subsurface and near-surface features of rocks. The magnetic method measures variations in the earth's magnetic field and have been used for various purposes such as in mineral exploration [1-4], geothermal studies [5-10], hydrocarbon exploration [11-13], archaeological investigations [14-16], depth to basement determination [17-19], estimating sedimentary thickness [20-22], environmental studies [23-25] and lots more. Aeromagnetic survey is able to quickly map difficult to access areas and covers a wider range than field geological mapping [26-28]. Aeromagnetic studies within the study area have been used mostly for mineral exploration [3-4,22,28, 9]. Thus, this study looks at magnetic sources, their distributions, structures and their trends, and depth estimates as it relates to hydrocarbon prospecting in parts of the southern Benue Trough and the Anambra Basin.

2. Geological setting

The study area lies in parts of the southern Benue Trough and the Anambra on latitudes 5°30' and 7°00'N, and longitudes 7°00' and 8°30'E, covering an area of approximately 23,570km^2 (Fig. 1), and ranges in age from Aptian to Maastrichtian (Table 1). The evolution of the Benue Trough and its sub-basins began in the Early Cretaceous with the breakup and separation of the African and South American plates, leading to the opening of the South

Atlantic Ocean [33]. This separation was initiated by the Y-shaped RRR triple-junction ridge system of which one arm failed to develop forming the Benue Trough [33-35]. The Benue Trough is divided into three main geographical segments: the northern Benue Trough, the central Benue Trough and the southern Benue Trough which is the most studied segment of the Benue Trough [36]. Within the southern Benue Trough, two phases of tectonic uplifts occurred. They are the sub-regional Cenomanian and regional Santonian thermotectonic event, which led to intense folding and faulting in the basin giving rise to the Abakaliki Anticlinorium and the Anambra Basin [37]. Rocks of the southern Benue Trough and the Anambra Basin are made up of igneous and sedimentary rocks. The igneous rocks occur as intrusives and are found in the southern Benue Trough and the basal units of the Nkporo Group of the Anambra Basin, in the Afikpo area. Sedimentary rocks within the southern Benue Trough and the Anambra Basin are assigned to three unconformity bounded depositional successions which are the Aptian-Cenomanian (Asu River Group-Mfamosing Formation), Turonian-Coniacian (Ezeaku and Awgu Groups) and Campanian-Maastrichtian (Nkporo Group, Mamu, Ajali and Nsukka Formations) cycles [38-39]. The Asu River Group is made up of shales, limestones and sandstone lenses belonging to the Abakaliki Formation of the southern Benue Trough, and limestones of the Mfamosing Formation in the Calabar Flank [40]. The marine Cenomanian Odukpani Formation forms the top of the Asu River Group and comprises of black shales, limestones and siltstones. The Ezeaku Group is of Turonian age and comprises of carbonaceous dark grey mudstones interbedded with marlstones that have rich marine organic matter. The Agala, Amasiri and Markurdi Sandstone are sandstone bodies within the Ezeaku Group. The Coniacian Awgu Group comprising of grey to dark, well-bedded fissile shales with thin beds of shelly limestones and marls conformably overlies sediments of the Ezeaku Group (Fig. 1). Occasional interbeds of fine to medium grained, moderately sorted sandstones also occurs in the Awgu Group. The Santonian is reckoned with the thermotectonic event which resulted in the folding and uplift of the trough to form the Abakaliki Anticlinorium and the Afikpo Synclinorium. The Anambra Platform subsided and the depocentre shifted southwards to the newly formed Anambra Basin and the Afikpo Synclinorium. The Nkporo Group is the basal unit of the Anambra Basin and overlies sediments of the southern Benue Trough in an angular unconformity. This basal unit is overlain by the Mamu, Ajali and Nsukka Formations [40-41].

Table 1. Tectonostratigraphy of the southern Benue Trough and the Anambra Basin (modified after [30-32]). UCM = Upper Coal Measure; LCM = Lower Coal Measure.

Age (Ma)	Period	Epoch	Age	Basin	Stratigraphy		Environment of Deposition	Events		
					Group	Formation /Member				
70	Cretaceous	Late	Maastrichtian	Anambra Basin	UCM LCM	Nsukka Fm. Ajali Fm. Mamu Fm.	Deltaic-Marine	Uplift of the Hoggar Massif, Southern Chad, Northern Benue Trough, and Onitsha High, (80 Ma)	Anambra Basin Fill	Drift
80			Campanian		Nkporo Group	Enugu Fm. Owelli Fm. Nkporo Fm.				
			Santonian	Intense Compression Leading to Inversion and Formation of the Abakaliki Anticlinorium						
			Coniacian	Southern Benue Trough	Awgu Group	Awgu Shale Agbani Sst.	Marine	Separation of the African and South-American plates	Abakaliki Rift	Transition
90			Turonian		Ezeaku Group	Amaseri Sst. Nkalagu Lst. Ezeaku Shale				
100			Cenomanian		Mfamosing Fm.					Rift
110		Early	Albian		Asu River Group	Abakaliki Fm. Awi Fm. Ogoja Sst.	Alluvial-Fluvial Lacustrine			
			Aptian							
Precambrian				Basement Complex						

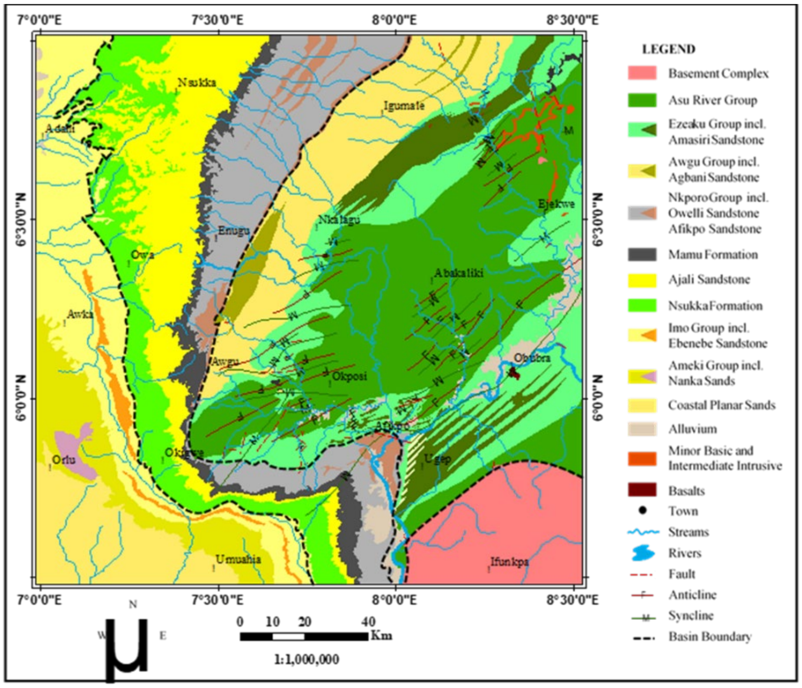


Fig. 1. Geologic map of the study area in parts of the southern Benue Trough and the Anambra Basin (modified from SHELL-BP [30]).

3. Materials and methods

The high-resolution aeromagnetic data were obtained over the study area by Fugro Airborne Surveys between 2005 and 2009, for the Nigerian Geological Survey Agency (NGSA). The survey has flight line of 500m and tie-line of 5,000m with an elevation of 80m, and follows the NW-SE flight line direction which is perpendicular to the axis of the trough. Preliminary processing of the aeromagnetic data was carried out by Paterson, Grant and Watson Limited (PGW), who reduced, gathered, merged and released the data in digital formats. The aeromagnetic sheets used are nine and comprises of sheets 287-Nsukka, 288-Igumale, 289-Ejekwe, 301-Udi, 302-Nkalagu, 303-Abakaliki, 312-Okigwe, 313-Afikpo, and 314-Ugep.

The raw aeromagnetic data was processed and corrected for latitude, diurnal and height variations using Geosoft® Oasis Montaj™ (Standard edition version 6.4.2 (HJ)). Then, the Total Magnetic Intensity grid of the study area was generated. Filters were applied to the TMI to generate Reduction to the Equator (RTE), Reduction to the Equator Inverted (RTE_INV), First Vertical Derivative (1VD), Second Vertical Derivative (2VD), Tilt-Derivative (TDR), Analytic Signal (AS) and Source Parameter imaging (SPI) grids. These grids were used to produce maps on a scale of 1:1,386,097 from the map tool menu of Oasis Montaj, and exported to ArcGIS Desktop 10.5 and Microsoft packages for further processing, enhancement and interpretations. Apart from the SPI measured in metres (m), other maps produced are measured in nano Tesla per kilometre (nT/km).

4. Results and discussions

4.1. Total magnetic intensity (TMI)

The TMI ranges from -51.60 to 151.25nT/km (Fig. 2). Amplitudes of magnetic anomalies accounts for the various colours observed on the TMI map. The blue colour indicates low magnetic anomalies and range from below -51.60 to 21.62nT/km, green indicates intermediate anomalies and range from above 21.62 to 48.47nT/km, red and magenta colours indicate high magnetic anomalies and range from 76.79 to above 151.25. The TMI does not give a true representation of intensities of magnetic anomalies of rocks in the subsurface and near-surface. Thus, the TMI map was processed to generate the RTE map.

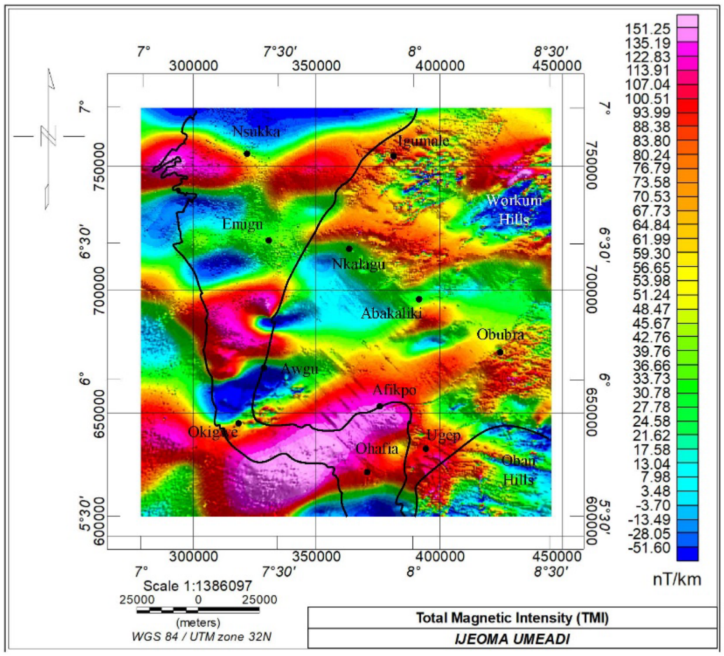


Fig. 2. Total magnetic intensity (TMI) map of the study area. ● Town; — Basin boundary.

4.2. Reduction to the equator (RTE)

The reduction to the equator (RTE) was used instead of the reduction to the pole (RTP) since the study area lies within the low magnetic latitudes [42-43]. The RTE places peaks of magnetic anomalies over their respective sources [42,44-46] and displays minor enhancement of magnetic anomalies of the TMI grid. The RTE map of the study area (Fig. 3) show low magnetic anomalies represented in blue colour range from below -48.57 to 22.67nT/km and covers areas around Workum Hills, north of Abakaliki, north of Nsukka, nortwestern Enugu, Awgu and south of Ohafia areas.

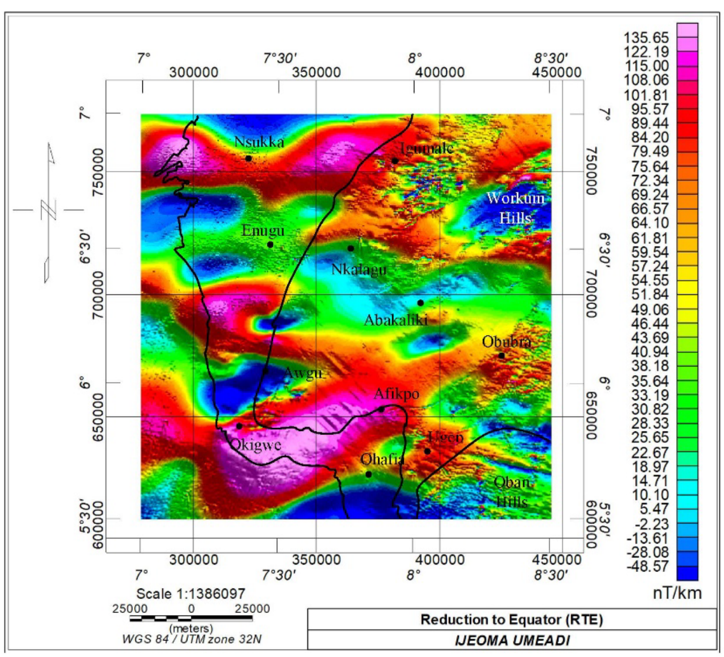


Fig. 3. Reduction to the Equator (RTE) map of the study area. ● Town; — Basin boundary.

Intermediate magnetic anomalies represented in green colour range from above 22.67 to 43.69nT/km, and covers the Enugu, parts of Abakaliki and west of Afikpo area. High magnetic anomalies represented in red and magenta colours were observed in west and east of the south of Nsukka, north of Awgu, north of the Workum Hills, north of Nkalagu, southwest of Afikpo and south of Okigwe areas, and range from 57.24 to above 135.65nT/km. The RTE was further processed to generate the RTE_INV map which gives better enhanced images.

4.3. Reduction to the equator inverted (RTE_INV)

The RTE_INV gives better representation of structures/features and anomalies within the study area (Fig. 4a).

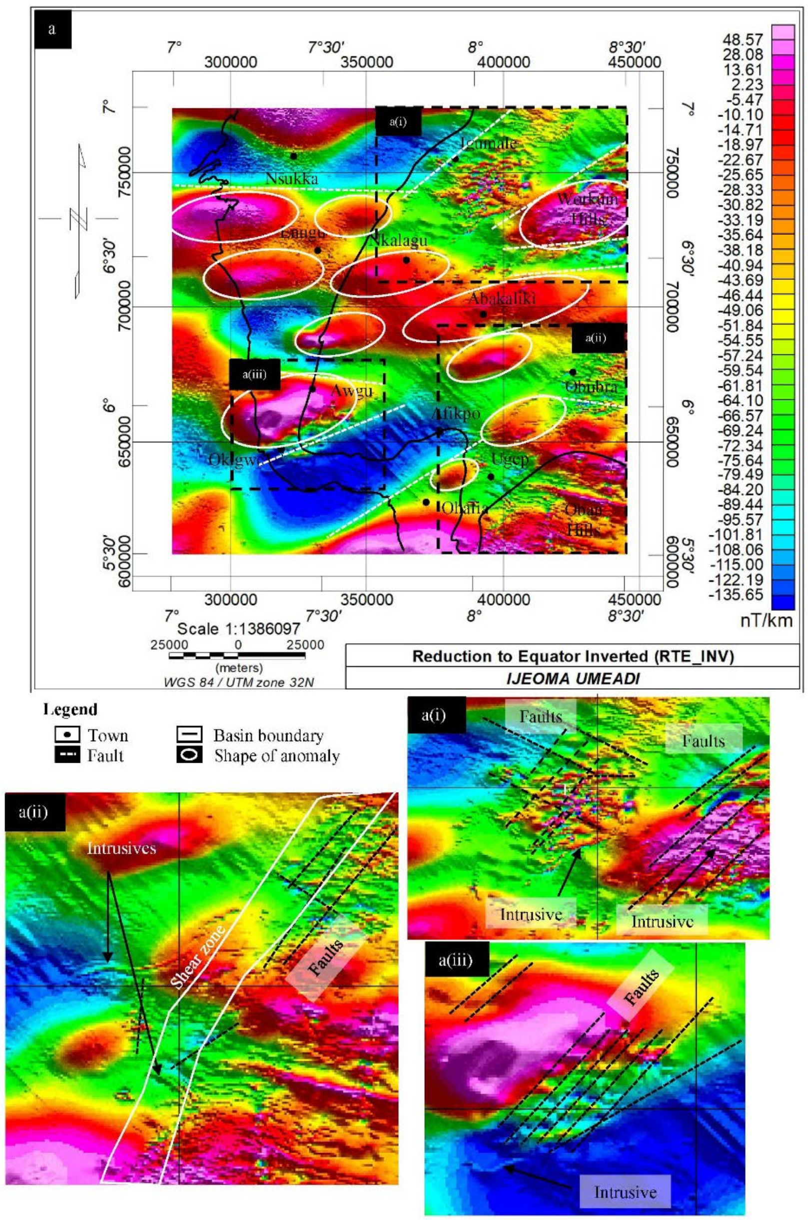


Fig. 4. (a) Reduction to the equator Inverted (RTE_INV) map of the study area showing oval-shaped anomalies and faults (a(i)) Faults and intrusives in the Igumale and Workum Hills areas (a(ii)) Intrusives, faults and shear zones in the Afikpo, Obubra and Ugep areas (a(iii)) Numerous faults and intrusive observed in the Awgu and Okigwe areas. ● Town; ─ Basin boundary; ‒‒ Fault; ⬭ Shape of anomaly.

Low magnetic anomalies represented in blue colour range from below -135.65 to -79.49nT/km, and were observed to the west and east of Nsukka, northwest of Awgu, south-west of Afikpo and south of Okigwe areas. Intermediate magnetic anomalies represented in green colour were observed in the areas surrounding Igumale, Workum Hills, Ugep and Obubra. Intermediate magnetic anomaly values range from above -79.49 to -54.55nT/km. High magnetic anomalies indicating magnetic sources are represented in red and magenta colours and occur more in the southern Benue Trough. They vary from -40.94 to above 48.57nT/km, and are prevalent in the north of Afikpo, Workum Hills, Nkalagu, Abakaliki, Enugu, south of Awgu, north of Okigwe and Ohafia areas. Oval-shaped magnetic anomalies trending mostly in the northeast-southwest directions, faults, shear zones, intrusives and ridges were also observed (Figs. 4a(i), a(ii) and a(iii)). These structures occur more in the northeastern and southeastern parts of the study area which lies within the southern Benue Trough.

4.4. First vertical derivative (1VD)

The 1VD is an edge detection technique that sharpens edges of magnetic anomalies and enhances shallow sources (Fig. 5a). The 1VD easily identifies areas of volcanic and igneous activities which were identified and labelled 1 to 5 (Fig. 5a).

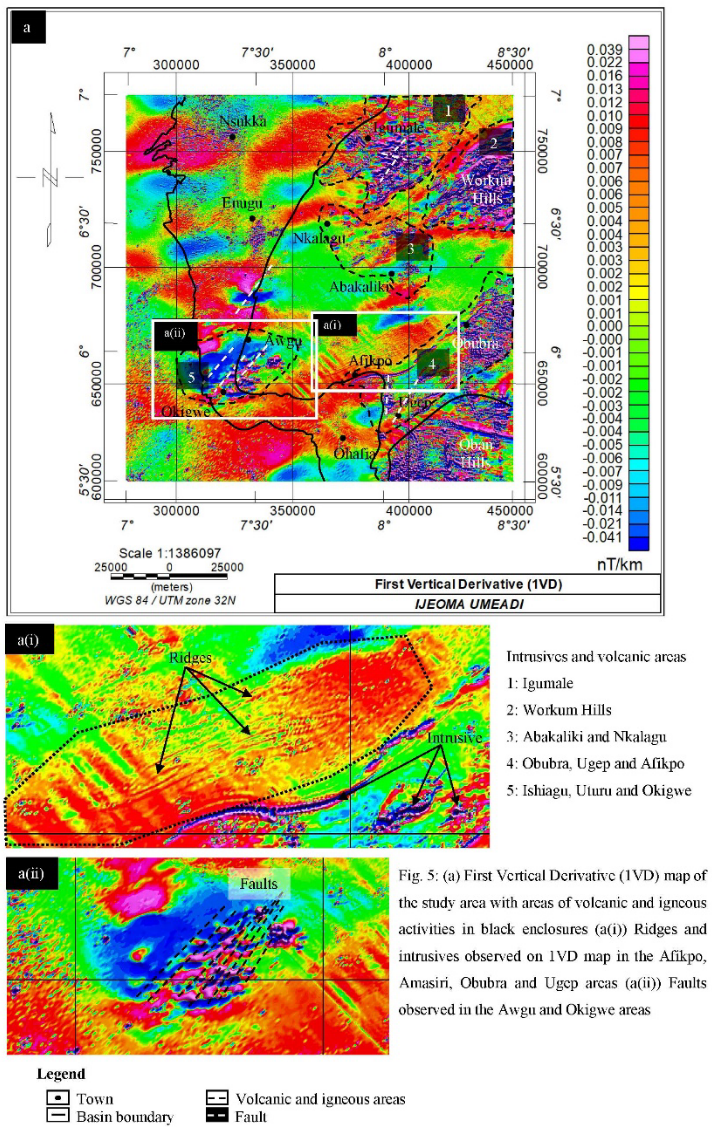


Fig. 5: (a) First Vertical Derivative (1VD) map of the study area with areas of volcanic and igneous activities in black enclosures (a(i)) Ridges and intrusives observed on 1VD map in the Afikpo, Amasiri, Obubra and Ugep areas (a(ii)) Faults observed in the Awgu and Okigwe areas

These areas on the map have mottled appearance and dominate the northeast and south-eastern sections of the map. Magnetic sources were observed to occur more in the southern Benue Trough. Low magnetic anomalies indicated in blue colour vary from below -0.041 to -0.004nT/km on the 1VD map. Intermediate indicated in green colour vary from above -0.004 to 0.001nT/km, while high magnetic anomalies indicated in red and magenta colours vary from 0.003 to above 0.039nT/km. Structures such as faults, ridges, intrusives and volcanic areas were observed in the 1VD map. The ridges, intrusives and faults trend in the northeast-southwest direction (Figs. 5a(i) and 5a(ii)), which is the dominant trend in the Benue Trough.

4.5. Second vertical derivative (2VD)

The 2VD also sharpens the edges of magnetic anomalies and improved resolution of closely spaced magnetic sources than the 1VD [46-47]. Magnetic sources occur more in the southern Benue Trough (Fig. 6a). Low magnetic anomalies indicated in blue colour vary from below -0.000233 to -0.000014nT/km, intermediate indicated in green colour vary from above -0.000014 to -0.000001nT/km, while high magnetic anomalies indicated in red and magenta colours vary from 0.000003 to above 0.000230nT/km. Areas of volcanic and igneous activities were identified and labelled 1to 5 in fig. 6a.Structures observed on the 2VD map are similar to those observed on the 1VD map. They are faults, ridges, intrusives and volcanic areas (Figs. 6a and a(i)). Above the 2VD, the noise becomes more pronounced than the signal thereby producing blurred images [49-49].

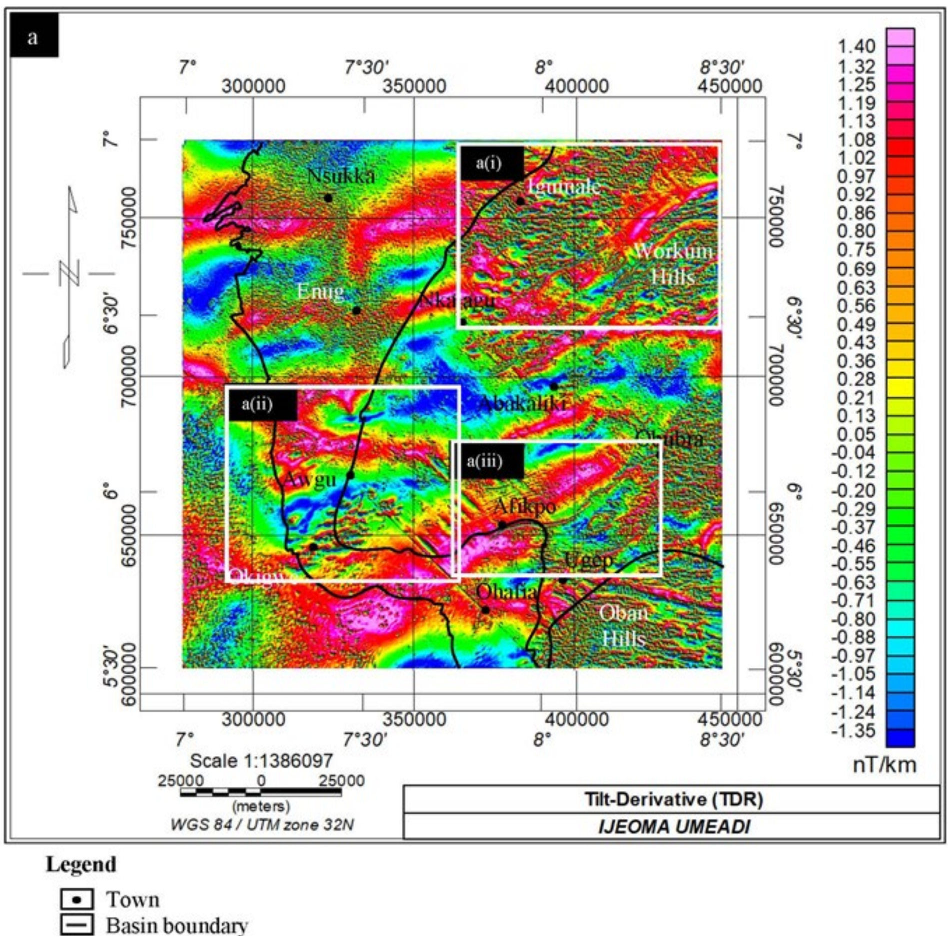
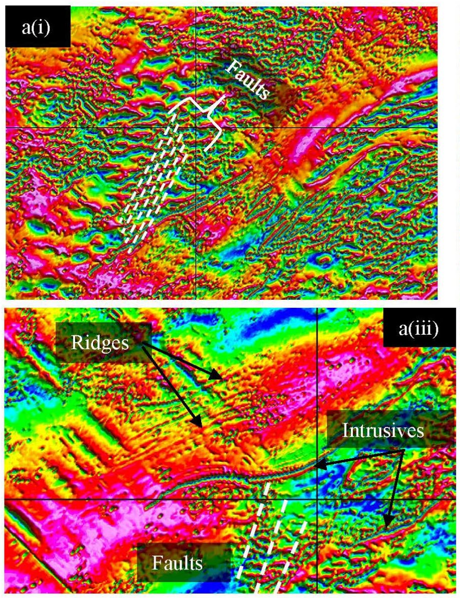


Fig. 6. (a) Tilt-Derivative (TDR) map of the study area (a(i)) Faults in the Awgu, Okigwe, Uturu and Ishiagu areas (a(ii)) Faults in the Igumale and Workum Hills areas (a(iii)) Ridges, intrusives and faults observed in the Afikpo and Ugep areas.

4.6. Total horizontal derivative (TDR)

The TDR map of the study area shows enhanced edges of shallow and deep magnetic sources (Fig. 7a). TDR shows better enhanced structures than the 1VD and 2VD maps. The study area is characterized by low magnetic anomalies that range from -1.35 to -0.63nT/km, intermediate range from above -0.63 to 0.21nT/km and high magnetic anomalies range from 0.43 to above 1.40nT/km. Ridges, faults, intrusives and volcanic areas were observed in the TDR map (Figs. 7a, a(ii) and a(iii)). These structures were also observed on the 1VD and 2VD maps and occur more in the southern Benue Trough.



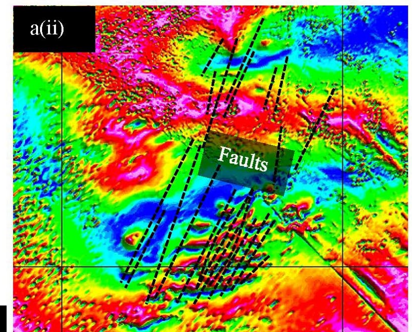


Fig. 7: (a) Tilt-Derivative (TDR) map of the study area (a(i)) Faults in the Awgu, Okigwe, Uturu and Ishiagu areas (a(ii)) Faults in the Igumale and Workum Hills areas (a(iii)) Ridges, intrusives and faults observed in the Afikpo and Ugep areas

4.7. Analytic signal (AS)

The AS developed by Nabighian [48,50], is perfect for locating magnetic sources. Distribution of magnetic sources in the subsurface within the study area is shown on the AS map (Fig. 8a). The AS map shows magnetic anomalies vary from low represented in blue colour, to intermediate in green colour and high in red and magenta colours. Low magnetic anomalies range from below 0.002 to 0.006nT/km. Intermediate from above 0.006 to 0.009nT/km, while high magnetic anomalies vary from 0.012 to above 0.103nT/km. Magnetic sources were observed in the Igneous and volcanic areas and labelled 1 to 5 (Fig. 8a). These areas show high magnetic anomalies with values above 0.023nT/km, while alluvium and sedimentary areas show intermediate to low magnetic anomalies with values below 0.002nT/km. Highest magnetic sources are located in the northeastern and southeastern parts of the study area which lies in the southern Benue Trough. A few other magnetic sources are located in other parts of the study area. Faults, ridges and intrusives were identified in figs. 8a(i) and 8a(ii).

4.8. Source parameter imaging (SPI)

The SPI gives depth ranges to various magnetic sources [51-53]. Within the study area, shallow depth represented in red and magenta colours range from -303.52 to above -168.78m (Fig. 9). Greater depth represented in green colour range from -1053.53 to -602.59m, while deepest parts have values greater than -1053.53m. Areas with shallow depth have shallow magnetic bodies and thin sedimentary pile. These shallow depths are observed mostly in areas of intrusives and volcanic areas such as the Igumale, Workum Hills, eastern sides of Nkalagu and Abakaliki, Obubra, Ugep, north of Afikpo, north of Ohafia, Ishiagu, northeast of Okigwe, Enugu and Nsukka areas. The deepest parts have the deepest magnetic bodies, thickest sedimentary pile, and are observed in the north of Nkalagu, west of Abakaliki, Awgu, south of Afikpo, areas surrounding Okigwe and Ohafia. These areas have been labelled as Target Areas

1, 2, and 3, and exceed the 1000m recognized by Benkhelil *et al.*, [54] and Hunt [55] as the sediment thickness required for a potential basin if all other petroleum system elements are present.

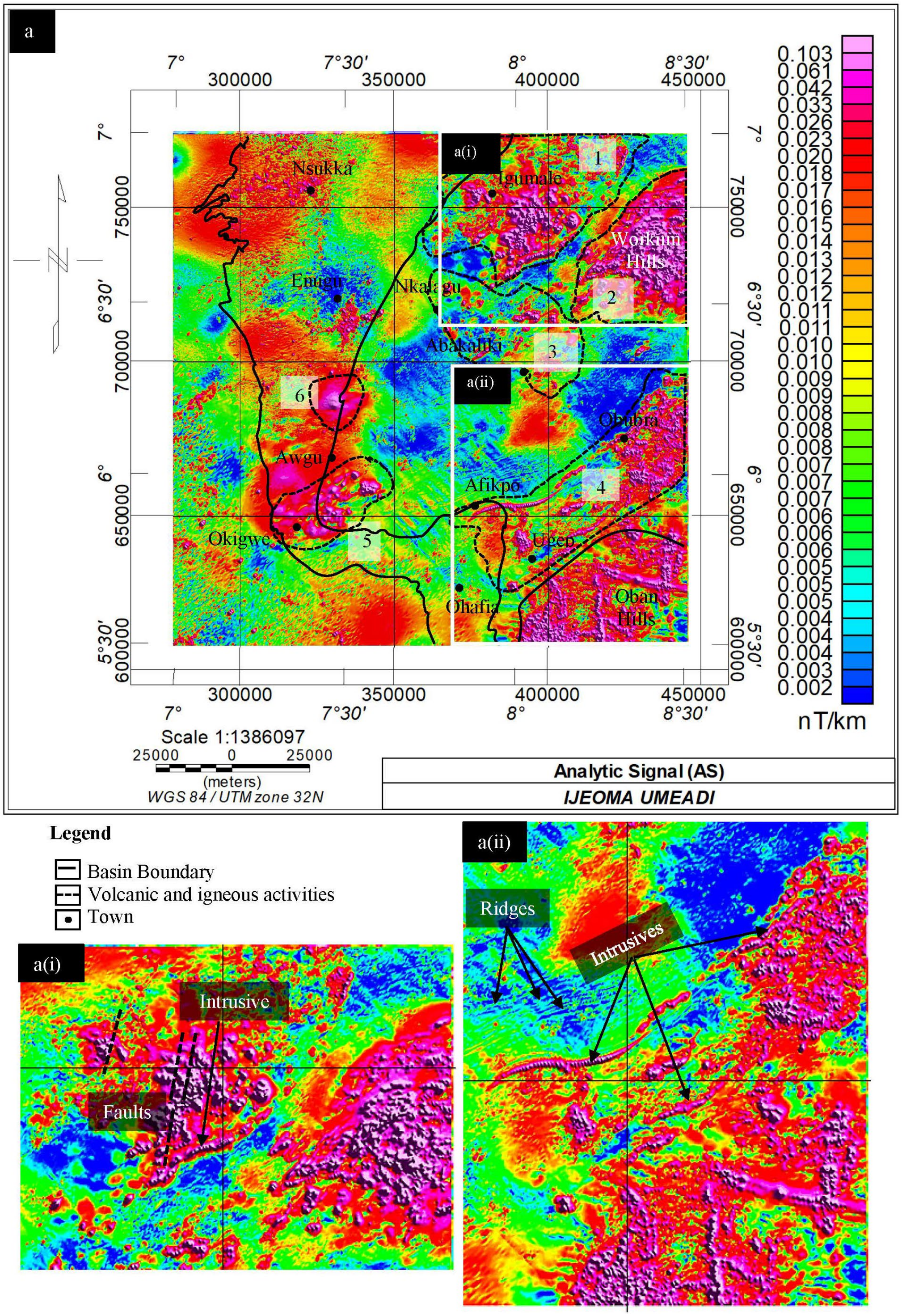


Fig. 8. (a) Analytic Signal map of the study area showing magnetic sources labelled 1-6.
1: Igumale area; 2: Workum Hills; 3: Abakaliki and Nkalagu areas; 4: Obubra, Ugep and Afikpo areas ; 5: Ishiagu, Uturu and Okigwe areas.
(a(i)) Faults and intrusives observed on the AS map in the Igumale and Workum Hills areas (a(ii)) Intrusives in the Obubra, Ugep and Afikpo areas, and ridges in the Amasiri and Afikpo areas.

5. Implications on hydrocarbon prospectivity

In hydrocarbon prospecting, areas of high magnetic anomalies (red and magenta colours) are not usually of interest as high magnetic anomalies indicate rocks with high proportions of magnetic minerals which is common in crystalline rocks, shallow depth to magnetic sources and thinner sedimentary pile (Figs. 4a, 5a, 6a and 8). Rocks of low magnetic anomalies (blue colour) are usually the target. They are usually sedimentary rocks and poorly consolidated sediments, have greater depth to magnetic sources and thicker sedimentary pile [54-57]. Areas of low magnetic anomalies in the northern and southern parts of the study area were observed to have greater depth to magnetic sources as observed in the RTE_INV (Fig. 4a) and SPI (Fig. 8) maps. Oyawoye [60], Adegoke and Omatsola [61], confirmed that areas of high magnetic anomalies are associated with tectonic activities which occurred during the Pan-African orogeny. Faults observed in figs. 4, 5a and a(ii), 6a, 7a(i), a(ii), a(iii), 8a(i), form excellent migration pathways and seals for hydrocarbon. Shear zones are usually intensely deformed and have fractures, faults and folds for trapping and expelling hydrocarbon. Intrusives are observed to be numerous in the southern Benue Trough. These intrusives provide heat needed for source rock maturation, but its presence in large quantities lead to overmaturation of source rocks. Ridges observed have been confirmed from various field studies to be sandstone ridges with swales made up of shales between each ridge [62-64]. These sandstone ridges serve as suitable reservoirs for hydrocarbon accumulation. Sediment thicknesses using the SPI (Fig. 9), identified three target areas (Target Area 1, Target Area 2 and Target Area 3). The target areas have sediments thicknesses that exceed 1000m required for a potential basin if all other petroleum system elements are present [54-55]. Integrating these maps, target areas 1 and 3 have better hydrocarbon potentials than target area 2.

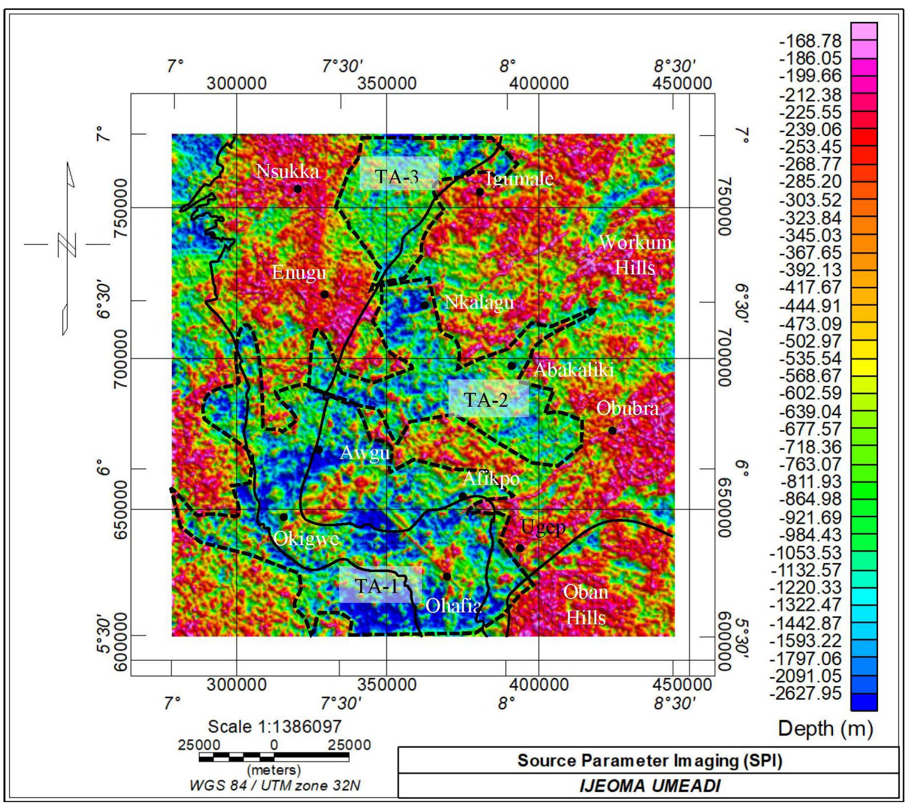


Fig. 9. Source Parameter Imaging (SPI) map of the study area with areas divided into Target Area 1, Target Area 2 and Target Area 3. • Town; — Basin boundary; - - Target areas.

6. Conclusion

High-resolution aeromagnetic and depth studies were carried out in parts of the southern Benue Trough and the Anambra Basin using TMI, RTE, RTE_INV, 1VD, 2VD, TDR, AS and SPI maps. These maps revealed the presence of rocks of high, intermediate and low magnetic anomalies within the study area. Rocks of high magnetic intensities are crystalline rocks while low magnetic intensities are sedimentary and poorly consolidated rocks. Rocks of high magnetic anomalies were observed more in the southern Benue Trough. Areas of high magnetic anomalies usually have shallow depth to magnetic sources and thinner sedimentary piles, while areas of low magnetic anomalies usually have greater depth to magnetic sources and thicker sedimentary piles. Structures observed are faults, ridges, shear zones, intrusives and volcanic activities. Some of these structures serves for accumulation of hydrocarbon and provides migration pathways for hydrocarbon. Intrusives provides heat needed for source rock maturation which in large quantities leads to overmaturation of source rocks. Areas with thick sedimentary piles (above 1000m thick) were identified and labelled as target areas 1, 2 and 3. Of these target areas, 1 and 3 have better potentials for hydrocarbon prospecting than 2.

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