

INTEGRATED GEOPHYSICAL INVESTIGATION OF SUBSURFACE STRUCTURES AND GROUNDWATER POTENTIAL IN IPOGUN DRAINAGE BASIN, SOUTHWESTERN NIGERIA

Faleye, E. T.^{1*}, Olorunfemi, M. O.², Akinwumiju, A. S.³, Oni, A. G.² and Bamidele, O. E.⁴

¹Dept. of Physical and Chemical Sciences, Elizade University, Ilara-Mokin, Ondo State, Nigeria.

<https://orcid.org/0000-0003-3375-504X>

²Dept. of Geology, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria.

mlorunfe@yahoo.co.uk; <http://orcid.org/0000-0003-3494-3333>

oniademakinwa@yahoo.com; <http://orcid.org/0000-0003-0627-7820>

³School of Architecture and Built Environment, University of Wolverhampton, Wolverhampton, West Midlands, United Kingdom.

⁴Dept. of Geophysics, Federal University Oye-Ekiti, Ekiti State, Nigeria. <http://orcid.org/0000-0003-4107-4738>

*Corresponding Author's Email: emmanuel.faleye16@gmail.com;

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ABSTRACT

Public water supply within the Ipogun Drainage Basin is grossly inadequate and in most towns nonexistent. Attempts at mitigating the inadequacy through drilling of shallow/moderately deep boreholes have met with challenges of low ($< 1 \text{ l/s}$) groundwater yields and failed boreholes, suspected to be due to poor knowledge of the subsurface sequence and the structural setting. This has necessitated a detailed assessment of the groundwater potential of the basin using an integrated geophysical technique. Ground magnetic profiling at 10 m spacing; long spread 2D Dipole-Dipole resistivity imaging with dipole length of 20 m; and forty-eight large spread Schlumberger Vertical Electrical Soundings (VESs) were carried out along six traverses ranging in lengths from 1.12-4.51 km that cut across prominent remote sensing/aeromagnetic derived lineaments. The magnetic anomalous zones were used to constrain the locations of the Dipole-Dipole profiles while the 2D resistivity images influenced the locations of the VES stations. The magnetic intensities varied between -761 and +636 nT. Thin and thick dyke magnetic anomalies were observed. The characteristics of the magnetic modelled fault/fractured zones include thin-to-moderate overburden thicknesses ($< 20 \text{ m}$), width extent of between 20 and 255 m and vertical/near-vertical dip. The 2D resistivity model-delineated-fault/fractured zones correlated well with the magnetic anomalous zones with width extent of between 40 and 250 m and depth extents $> 100 \text{ m}$. Four geoelectric layers comprising the topsoil/laterite, weathered layer, partly weathered/fractured basement and the fresh basement were delineated. The partly weathered/fractured aquifer has resistivity and thickness ranges of between 25 and 1472 ohm-m and 4.5 and 117 m respectively. The weathered layer and partly weathered/fractured layer are the major aquifer units with the latter having a percentage of occurrence of 56.25% as against 43.75% for the former, indicating prospect for higher groundwater potential due to enhanced transmissivity and porosity of the partly weathered/fractured basement columns. This was corroborated by an increased groundwater yield of 1.4 l/s from a 60 m deep borehole drilled within one of the resistivity anomalous zones which penetrated the weathered layer aquifer and the upper segment of the partly weathered/fractured basement. It is concluded that the basin has prospect for high groundwater potential, in areas where the basement is weathered and fractured to deep depth, and the fractures are interconnected over a large area, to influence transmission and storativity of the groundwater. Recommended drilling depths may exceed 100 m compared with previous reliance on relatively shallow boreholes.

Keywords: Magnetic modelling, 2D Resistivity Imaging, Vertical Electrical Sounding, Sustainable Groundwater Yield, Ipogun Drainage Basin.

INTRODUCTION

The water resources of the world are broadly classified as surface and groundwater (Olorunfemi, 2008). The surface waters in streams, rivers and lakes are susceptible to pollution through anthropogenic activities and natural geological processes and are generally of poor quality (United Nations, 1997; Mostafa *et al.*, 1999; Goni, 2006; Simon-Oke *et al.*, 2014; Dada, 2015; WHO, 2016). However, infiltrated groundwater through natural ground filtration process is generally of better quality (Mostafa *et al.*, 1999; Simon-Oke *et al.*, 2014;

WHO, 2016). In Denmark, Malta, Saudi Arabia, etc. groundwater constitutes the main source of potable water supply. In Tunisia, it accounts for 95% of the country's total water resources, 83% in Belgium, and 75% in the Netherlands, Germany and Morocco. In most European countries (Austria, Belgium, Denmark, Hungary, Romania and Switzerland) groundwater's use exceeds 70% of the total water consumption (UNESCO 2004).

In Nigeria, more than 70% of the available potable water is groundwater (Ali, 2012). However, poor

understanding of the variability of its occurrence, particularly in the basement complex terrain, constitutes a barrier to its development (Akinwumiju and Olorunfemi, 2016). The intermittent nature of the basement aquifer system makes acquisition of detailed knowledge of the weathering depth, its lateral extent and structural disposition, from geological and geophysical investigations, inevitable (Adiat *et al.*, 2009; Bayowa *et al.*, 2014; Bayewu *et al.*, 2017).

The Ipogun Drainage Basin, located in the northwestern part of Ondo State, Nigeria (Figure 1), has witnessed rapid infrastructural development due to the establishment of several governmental institutions including a radio station, high court, civil service training institute, hospital, a close by Federal University of Technology, Akure, and a privately owned Elizade University, Ilara Mokin. This has led to an increase in human population and a consequent rise in safe water demand for domestic and agricultural needs (Oni, 2016; Igbasan, 2016). The public water supply through the State Water Corporation has remained inadequate and in many towns within the basin, virtually non-existent. The inhabitants have had to seek alternative sources of potable water such as hand dug wells, shallow/deep boreholes, streams and rivers. The surface water sources are prone to pollution. Groundwater obtained from shallow hand dug wells is also prone to pollution through the bailing system and other anthropogenic activities. Groundwater abstracted from boreholes are generally fresh and have constituted a viable alternative to the inadequate public water supply. However, groundwater development through boreholes has witnessed cases of failures and extremely low groundwater yield in Ilara-Mokin, Igbara-Oke, Ero, Isarun (Oni, 2016; Igbasan, 2016). Audited records of existing (101) boreholes within the basin (Faleye, 2021) showed that productive boreholes with yield greater than, or equal to 1 litre per second ($\geq 1 \text{ l/s}$) are 17%, while

marginally-productive and abortive boreholes with yields of less than 1 litre per second accounted for 83%. The boreholes have optimum drill depths of generally $< 40 \text{ m}$. The results of the analysis of 100 secondary (previously acquired) VES data sets from the basin indicated that the weathered layer constitutes the major aquifer unit within this depth range. It also showed that the aquifer has generally low resistivity ($< 150 \text{ ohm-m}$) due to its clayey nature with low permeability and low groundwater yielding capacity. At this shallow depth, lineaments are few and far in between. The aforementioned may have accounted for the low groundwater yield. However, recent lineament mapping within the basin has established network of short length ($< 1 \text{ km}$), long length (up to 9 km) and shallow to deep seated (up to 300 m) lineaments within the basin (Faleye, 2021). Previous studies (Oni, 2016; Igbasan, 2016) that attempted to assess the groundwater potential of the basin have been very localised, not comprehensive and non-inclusive of the investigation of the influence of lineaments. This study, therefore, intends to assess the groundwater potential of the Ipogun Drainage Basin using the subsurface geoelectric characteristics and structures. The study will involve magnetic profiling for structure (lineament) mapping and 1D and 2D resistivity imaging for subsurface geoelectric sequence delineation, structure delineation and aquifer identification, and lineament confirmation, and the establishment of the hydrogeological significance of the magnetic delineated structures (lineaments) respectively.

STUDY AREA

Ipogun Drainage Basin lies between Latitudes $7^{\circ} 16'$ and $7^{\circ} 26'$ North and Longitudes $5^{\circ} 1'$ and $5^{\circ} 10'$ East (Figure 1). The basin covers Ifedore, Ile Oluji/Okeigbo and Akure South Local Government Areas of Ondo State, Nigeria, with an estimated area coverage of 163.7 km^2 .

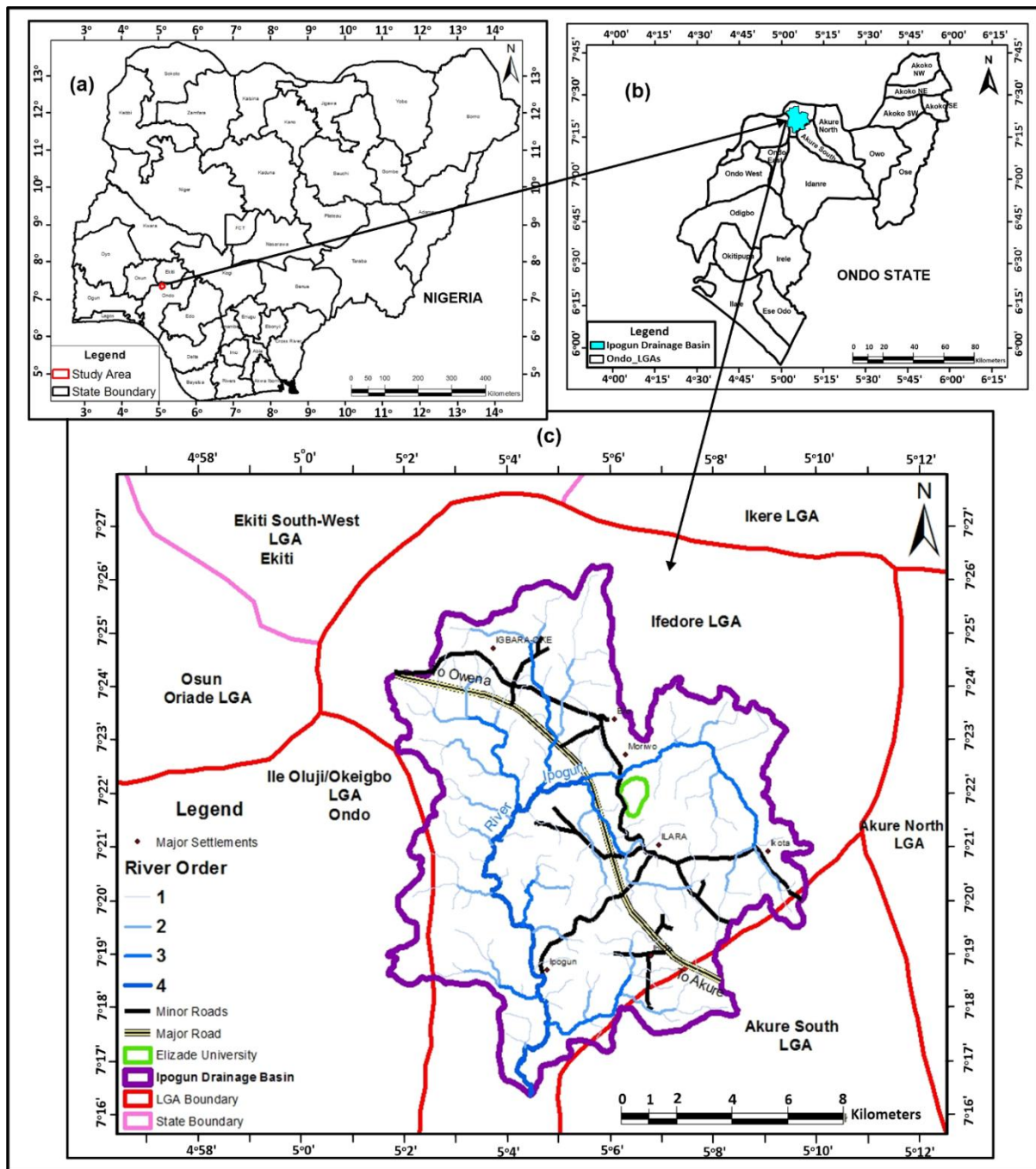


Figure 1: Administrative/drainage map of Ipogun Drainage Basin (culled from Faleye, 2021)

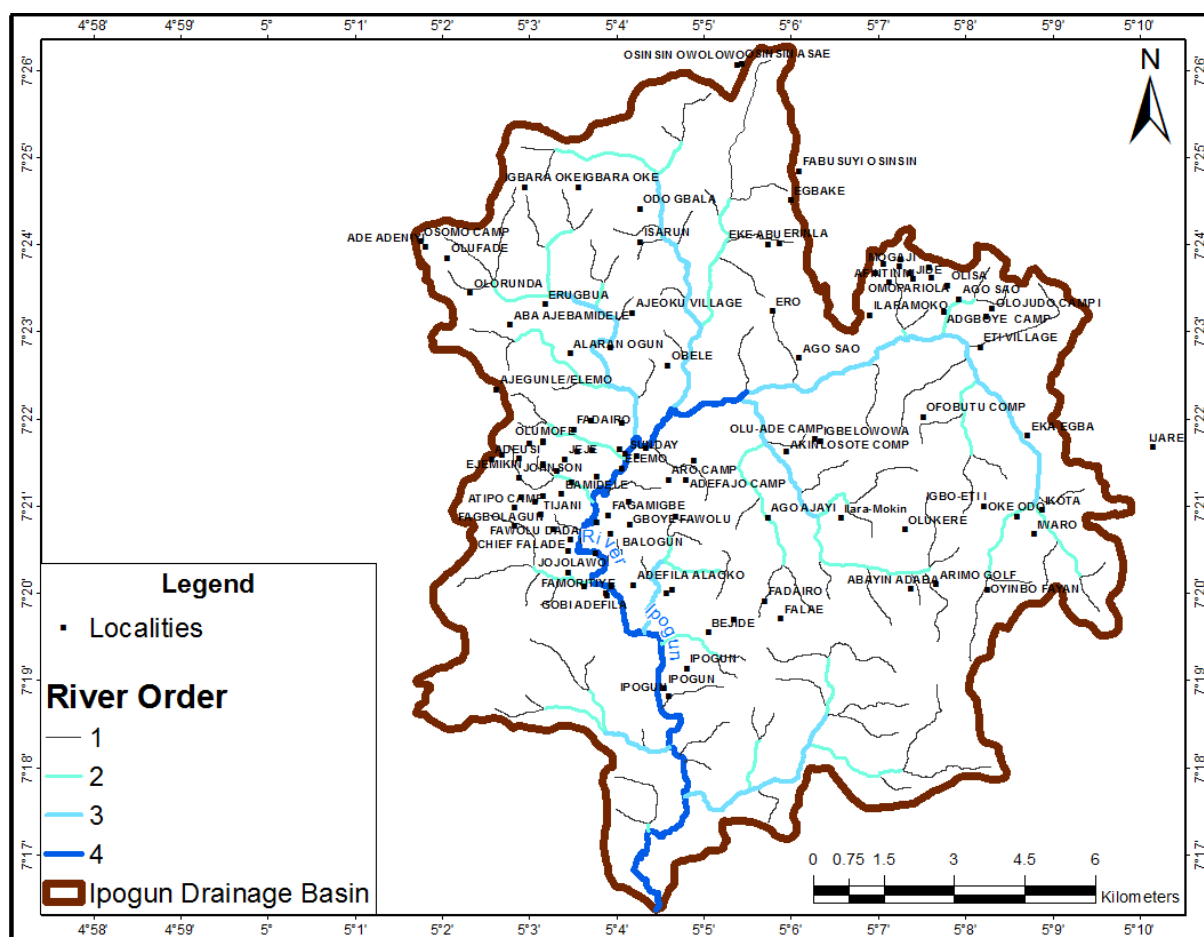


Figure 2: Map showing localities within the study area (culled from Faleye, 2021)

The major settlements within the study area are Igbara-Oke, Ilara-Mokin, Isarun, Ipogun and Ero. Other localities are Abayi, Adaba, Adetunla camp, Ajegunle Elemo, Ajogbolamu, Alaran Ogun, Ago Sao, Bejide, Fagbolagun, Ikota, Igbo-Eti, Iwaro, Moriwo, Obele, Olukere and Olorunda. The basin is dendritically drained by the Ipogun River and its tributaries (Figure 2).

The region lies within the tropical rainforest of Nigeria with two distinct seasons (wet from April to November and dry from December to March). The annual mean rainfall is about 1800 mm while the annual mean temperature ranges between 24 °C and 27 °C. Humidity is relatively high during the wet season and low during the dry season with a mean annual relative humidity of about 80% (NIMET 2007).

The area falls within the basement complex region of southwestern Nigerian and it is underlay by migmatite, quartzite and charnockitic meta-intrusive rocks (Figure 3) with the migmatite

covering about 75% of the basin (Akintorinwa *et al.*, 2011). The several localities underlain by the migmatite include Ipogun, Ilara-Mokin, Ero, Isarun, Igbara-Oke, Olorunda, Osomo Camp, Ago Sao, Erinla, Ajebamibele, Alaran Ogun and Moriwo. Outcrops of the rock are common within these localities, but are concealed in some parts, at shallow depth. The texture of the rock is medium to coarse grained. Quartzitic rock occupies very small portion (about 5%) of the study area. The Charnockitic meta-intrusive rock underlies about 20% of the study area (Figure 3).

The basement rocks are crystalline in nature with low porosity and permeability and generally low water-bearing capacity. However, the hydrogeological characteristics is enhanced when the rocks are weathered and or jointed/fractured (Bose *et al.*, 1973; Vandenberghe, 1982; Ako and Olorunfemi, 1989; Olorunfemi and Fasuyi, 1993; Afolayan *et al.*, 2004; Olorunfemi *et al.*, 2021).

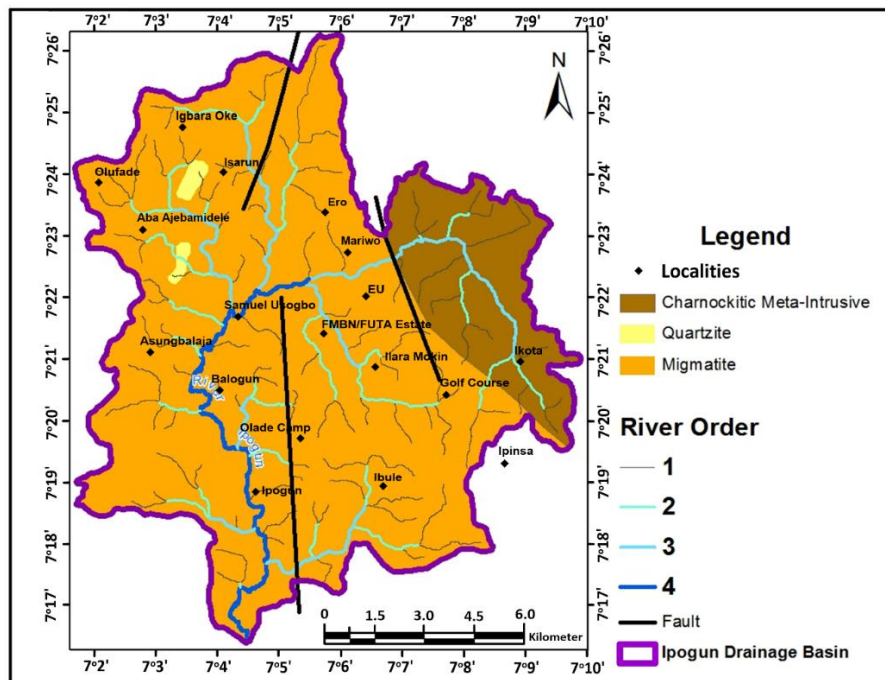


Figure 3: Geological map of the study area showing major suspected faults (modified after Akintorinwa *et al.*, 2011)

METHODS OF STUDY

An integrated remote sensing and aeromagnetic investigation of the study area (Faleye, 2021) resulted in the delineation of a network of lineaments whose hydrogeological significance is

yet to be established in order to properly assess the groundwater potential of Ipogun Drainage Basin. Ground magnetic profiling, 2D resistivity imaging and 1D VES techniques were carried out

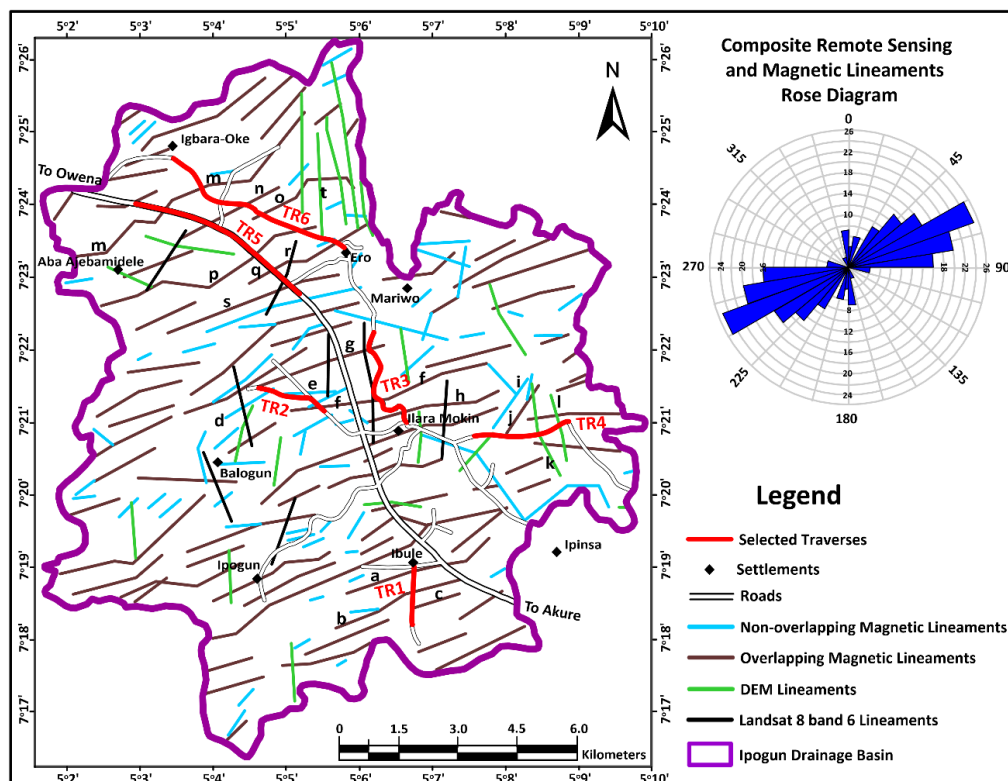


Figure 4: Selected traverses on the composite lineament map of Ipogun drainage basin with highlighted investigated lineaments (modified from Faleye, 2021)

along six selected traverses ranging in lengths from 1.12 km to 4.51 km, to ground truth some of the prominent aeromagnetic/remote sensing derived lineaments (Figure 4). The traverse orientations range from N-S, W-E, NW-SE to NNW-SSE. Magnetic profiling was done at 10 m spacing while the electrical resistivity survey involved twelve 2D Dipole-Dipole array subsurface imaging with 20 m dipole length and expansion factor, n , varying from 1 – 5, and forty-eight large spread (AB/2 of up to 350 m) Vertical Electrical Sounding (VES) involving the Schlumberger array. The VES locations were constrained by the 2D resistivity images. 2D modeling of the magnetic profiles was constrained with the 1D VES and 2D dipole-dipole imaging models.

The magnetic data acquisition followed standard procedures with diurnal and offset corrections effected. The corrected magnetic data were presented as profiles. All magnetic traverses were appropriately georeferenced. The GSM 19T Proton Precession Magnetometer, with 0.01 nT resolution and 0.2 nT absolute accuracy, was used for the magnetic data gathering. 2D modeling of the magnetic profiles was carried out using Oasis Montaj version 6.4.2 software and suspected basement structures (faults, fractures etc.) mapped. This was done to validate the remote sensing/aeromagnetic delineated lineaments and to identify other geological structures that could be of hydrogeological interest such as shear zones, basement depressions and lithological contacts.

The electrical resistivity survey was also carried out across the earlier selected major lineaments in order to corroborate the existence of the structural elements. The resistivity method utilized the 2D imaging technique involving large spread (400 – 860 m) profiles. Subsequently, Vertical Electrical Soundings were carried out on major structures that were identified from the inverted 2D Dipole-Dipole structures. The Dipole-Dipole data were presented as pseudosections while the VES data were presented as VES curves. All the Dipole-Dipole and VES stations were appropriately georeferenced. The Ohmega Campus Resistivity Meter was used for the data acquisition. The resistivity field data acquired for the 2D imaging profiling were subjected to 2D inversion with the DIPRO software (Dipro for Windows 2001). The software adopted an automated 2.5-dimensional smoothness-constrained least-square inversion

based on finite element approximation. Apart from information on the number of iteration and subsurface layers that were user-defined, most of the modeling input parameters were automatically determined or constrained. For these parameters, a value of 5 was input for each data set, with the later parameter based on the site-specific optimum number of delineated subsurface layers. The root mean square (rms) error, representing the inversion or the inverted image accuracy uncertainty, varied between 0.102 and 0.222. Suspected hydrogeological significant water bearing faults and fractured zones were characterized by low resistivity vertical/near vertical discontinuities within high resistivity fresh basement host rocks (Olorunfemi *et al.*, 2020; Ishola, 2026).

The VES data acquired were quantitatively interpreted using the partial curve matching technique. The preliminary interpreted geoelectrical parameters (layer resistivities and thicknesses) obtained were refined using WinResist Version 1.0 1D Forward modeling software. The software utilized the partial curve matching derived layer resistivities and thicknesses as starting model parameters to generate theoretical VES curve which was compared with the field curve. The model parameters are subsequently automatically modified and the process was repeatedly performed (a process commonly referred to as iteration) until the theoretically generated VES curve fitted the field curve to better than 95% (fitting error of $< 5\%$). The final VES interpretation results were used to generate the subsurface geoelectric sequence, identify aquifer units and structures and classify them.

The suspected structures interpreted from the 2D resistivity images were correlated with the magnetic profiles and the locations of intercepted remote sensing/aeromagnetic derived lineaments along each traverse line. This enabled the establishment of any relationship between the 2D derived structures and the lineaments and identify characteristic images from the Dipole-Dipole profiles. 2D geoelectric sections generated from the VES interpretation results and the 2D magnetic models were correlated to validate hydrogeologically relevant structures identified across the geophysical methods and techniques.

This synthesis enabled a better assessment of the groundwater potential of the study area.

RESULTS AND DISCUSSION

Results

The typical residual magnetic profiles are presented in Figure 5. The intensity of the total magnetic field varied from -761 to +636 nT. In low magnetic latitude region such as Nigeria, peak negative magnetic anomalies are typical of magnetic targets (Parasnis, 1986; Fieberg, 2002), including water saturated fault and fractured zones (Ojo *et al.*, 2011; Olorunfemi *et al.*, 2020). For groundwater investigation therefore, magnetic anomalies characterized by moderate to relatively high amplitudes with negative polarity, are of interest (Eniola, 2018; Olorunfemi and Oni, 2019; Bayowa *et al.*, 2024). The magnetic profiles are characterized by thin dyke (single peak negative

magnetic anomaly with low amplitude positive shoulders) and thick dyke (double peak negative (lows) with central high bounded by low amplitude positive shoulders) anomalies.

These magnetic signatures define fault zones with small and large width extents respectively (Olorunfemi *et al.*, 2020; Bayowa *et al.*, 2024). The negative polarity magnetic anomalies observed using the residual magnetic profiles and within the suspected fault/fractured zones are believed to be due to enhanced magnetic susceptibilities from deposited Fe ions released from the host basement rock into the groundwater during chemical weathering process. The 2D magnetic models (e.g. Figure 6) are characterized by thin-to-moderate overburden thicknesses that ranged between 0.2 and 33 m (but are generally < 20 m) with width extents of between 20 and 255 m (Table 1).

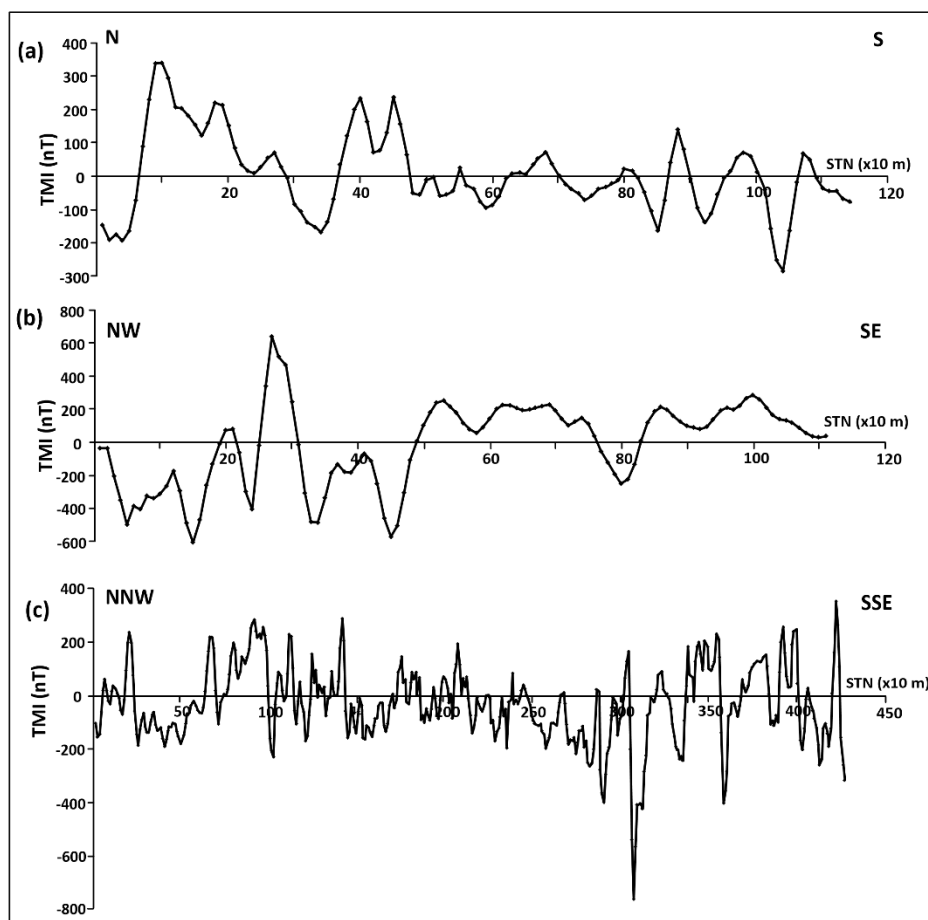


Figure 5: Residual magnetic profiles along Traverses 1, 2 and 3

Figure 7 shows the representative inverted 2D resistivity structures (images). The 2D structures delineated three subsurface layers classified as topsoil (laterite)/weathered layer, partly weathered/fractured basement and the fresh

basement. The topsoil (laterite)/weathered layer resistivity (in blue to green colour band) and depth extent are between 8 and 2836 ohm-m (but are generally < 350 ohm-m) and 2 and 50 m respectively. The partly weathered/fractured

basement (identified as the transition zone between the weathered and the fresh basement (in yellow colour band)) is characterized by resistivities and depth extent of between 61 and 1714 ohm-m (but are generally < 1000 ohm-m) and 3 and > 100 m respectively. The fresh basement (in red-purple colour band) is of high resistivity values > 700 ohm-m. The depth to basement rock head is relatively shallow (generally < 20 m) but significantly deep (up to or > 100 m)

beneath the fractured/faulted basement (Table 2). These parameters are similar to values obtained by Olorunfemi *et al.* (2020), Bayowa *et al.* (2024) and Bem *et al.* (2025) in a similar basement complex environment. Typical fault/fractured zones are characterized by low resistivity discontinuity within highly resistive host fresh basement rock (Olorunfemi *et al.*, 2020; Bayowa *et al.*, 2024; Maurya *et al.*, 2025 and Ishola, 2026). The relatively low resistivity values

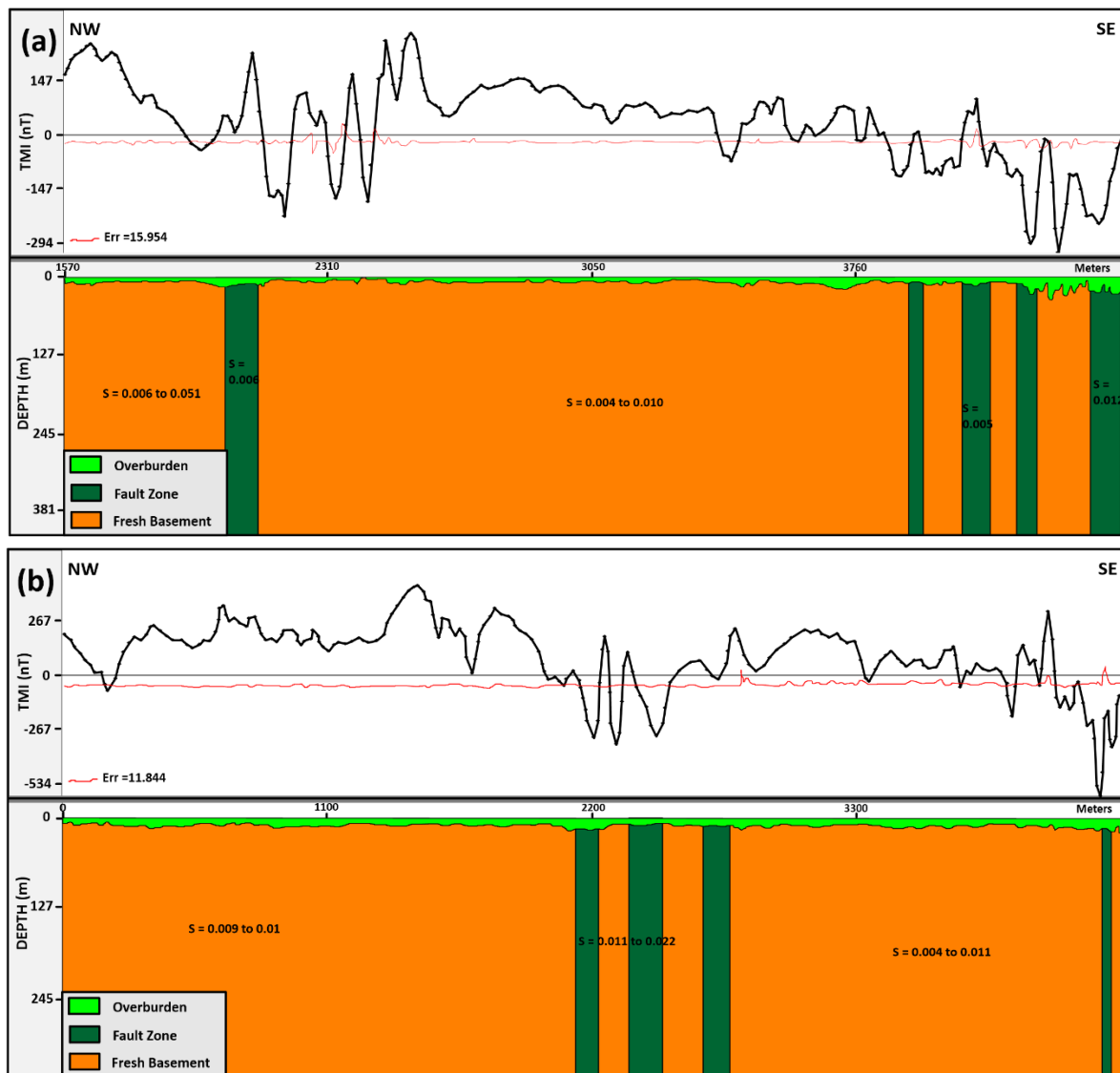


Figure 6: Residual magnetic profiles and 2D magnetic models along (a) Traverses 5 and (b) Traverse 6

(generally < 800 ohm-m) characterizing the partly weathered/fractured basement are diagnostic of fault/fractured zones. The geoelectric characteristics of the identified fault/fractured

zones are contained in Table 3. The significant depth and width extents of the 2D resistivity delineated structures suggest major or regional structures.

Table 1: Characteristics of magnetic profiles and 2D magnetic models

Traverse No	Magnetic Intensity (nT)	Typical Anomaly	Range of Overburden Thickness (m)	Width of Fault Block (m)	Attitude/Dip of Fault
1	-285 to +339	Thick dykes	0.2 – 25	27 – 116	Near Vertical
2	-596 to +636	Thick dykes	0.2 – 25	48 – 130	Near Vertical
3	-761 to +351	Thin/Thick dykes	3.5 – 33	20 – 125	Vertical
4	-182 to +371	Thin/Thick dykes	0.2 – 20	75 – 255	Vertical
5	-304 to +278	Thick dykes	0.2 – 10	31 – 93	Vertical
6	-614 to +446	Thick dykes	0.2 – 10	23 – 126	Vertical

Table 2: 2D resistivity structures' layer characteristics

Subsurface Layer	Resistivity Range (ohm-m)	Depth Range (m)
Topsoil/weathered layer	8 – 2836	2 – 50
Partly Weathered/fractured basement	61 – 1714	3 to > 100
Fresh basement	717 – 578208	20 to > 100

The VES curves ranged from simple 3 - 4 layer A, H, AA, HA, KH and QH type to complex 5-layer AKH and HKH type to more complex 6 – 7 layer HAKH, KHKH, QHKH and HKHKH type (Figure 8) associated with unconfined and confined fractured basement columns (Olorunfemi and Fasuyi, 1993). The H type curve is the most predominant, accounting for 27.08% of the total sounding curves. The VES interpretation results delineated four geologic layers comprising of topsoil/laterite, weathered layer, partly weathered/fractured basement and the fresh basement (Table 4).

Figure 9 displays representative geoelectric sections from the study area. The topsoil/laterite,

which is composed of clay, sandy clay, clayey sand, and laterite has resistivity values ranging between 56 and 938 ohm-m with highest frequency of < 400 ohm-m and thicknesses ranging between 0.2 and 4.6 m but are generally < 3.0 m.

The weathered layer resistivities and thicknesses ranged respectively between 19 and 520 ohm-m (with the highest frequency of < 150 ohm-m) and 0.5 and 25.7 m (but are generally < 10 m). The generally low resistivity values of the weathered layer is indicative of its clayey nature, low permeability and low groundwater yielding capacity. This may account for the low groundwater.

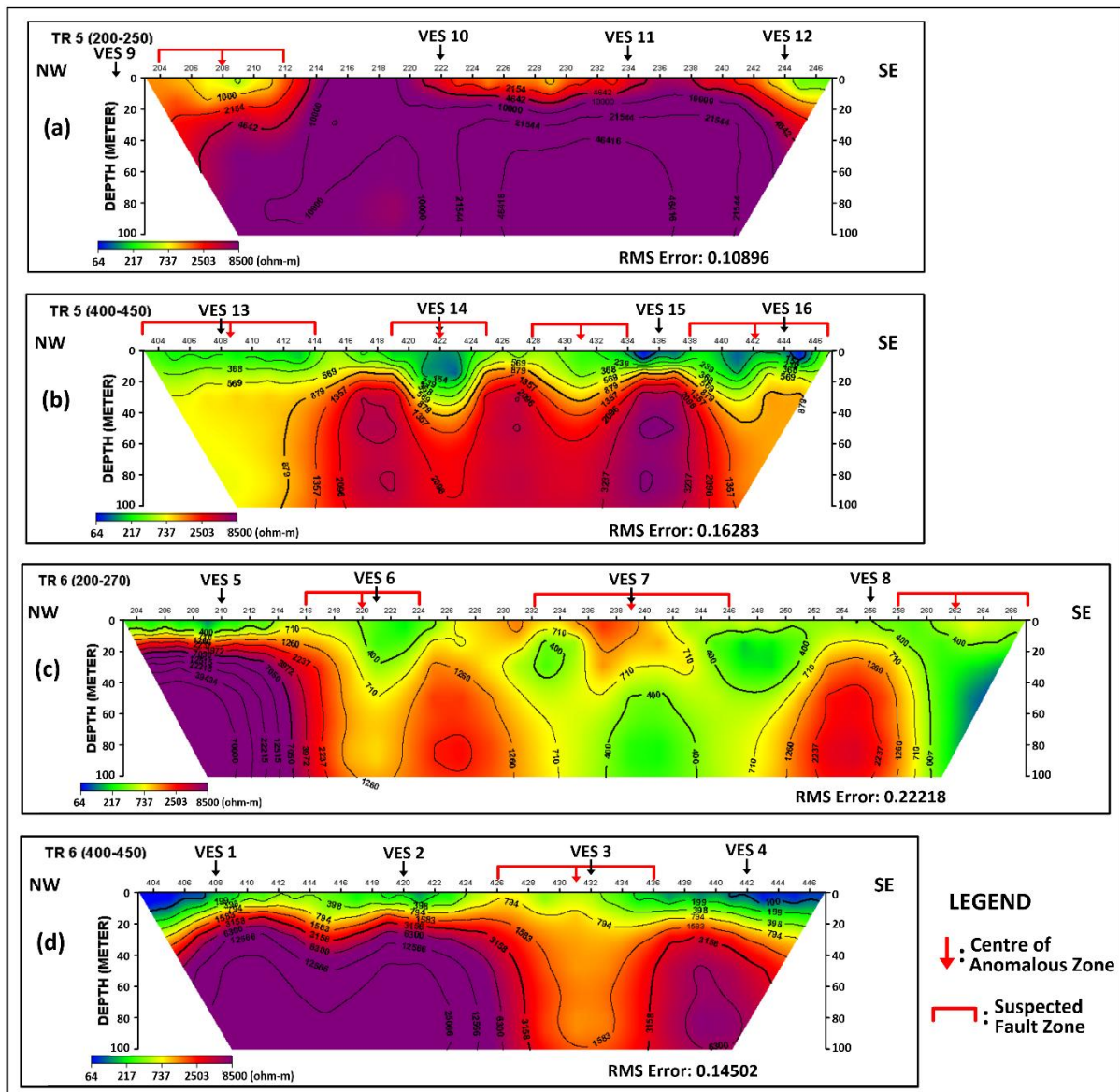


Figure 7: 2D Resistivity structures along Traverses 5 and 6

potential rating of wells and boreholes that abstract from the weathered column in the study area. The partly weathered/fractured basement is characterized by resistivity values ranging between 25 and 1472 ohm-m (but are generally < 400 ohm-m) with thickness values ranging between 4.5 and 117.2 m. The significant depth extent of delineated basement fault/fractured zones makes the structures hydrogeologically significant, most especially if water saturated. The fresh basement

resistivity values ranged between 420 and ∞ ohm-m (but are generally > 1000 ohm-m). The depths to rock head or overburden thicknesses ranged from 0.4 to 185.7 m. The delineated aquifer types are the weathered aquifer, weathered/fractured (unconfined) aquifer, weathered/fractured (confined) aquifer and the fractured (confined) aquifer which accounted for 43.75%, 6.25%, 33.33% and 16.67% occurrence respectively (Table 5).

Table 3: Characteristics of identified suspected fault/fracture zones

Traverse No/Stns.	Width of anomalous zone	Depth extent of anomalous zone
1 (Stns. 10-50)	Stns. 12-20 (80 m) & Stns. 38-44 (60 m)	> 50 m
1 (Stns. 78-120)	Stns. 94-98 (40 m) & Stns. 104-110 (60 m)	50 m

2 (Stns. 0-50)	Stns. 6-12 (60 m) & Stns. 17-26 (90 m)	> 100 m
2 (Stns. 60-110)	Stns. 67-83 (160 m) Stns. 90-96 (60 m)	> 100/60 m
3 (Stns. 120-200)	Stns. 156-164 (80 m)	> 100 m
3 (Stns. 300-360)	Stns. 306-322 (160 m) & Stns. 332-357 (250m)	> 100 m
4 (Stns. 110-160)	Stns. 114-130 (160 m) & Stns. 142-157 (150m)	> 100 m
4 (Stns. 200-286)	Stns. 200-210 (100 m) Stns. 236-260 (240 m) Stns. 278-286? (80 m)	> 100 m
5 (Stns. 200-250)	Stns. 204-212 (80 m) Stns. 242-250? (80 m)	20 m
5 (Stns. 400-450)	Stns. 400-414 (140 m); Stns. 415-425 (100 m); Stns. 428-434 (60 m) & Stns. 438-447 (90 m)	> 90 m
6 (Stns. 200-270)	Stns. 216-224 (80 m); Stns. 232-246 (140 m) & Stns. 258-266 (80 m)	> 100 m
6 (Stns. 400-450)	Stns. 426-436 (100 m)	> 100 m

Note: Stns. = Station numbers on 2D Resistivity Images (To convert to distances, multiply station numbers by 10).

In addition to the clayey content of the weathered layer aquifer, the unit is generally thin (Table 4). The weathered layer aquifer type is often of high porosity but low permeability resulting from its clayey nature, hence its low resistivity and low groundwater yielding capacity (Olorunfemi and Fasuyi, 1993; Dewandel *et al.*, 2006; Gao *et al.*, 2018; Hasan *et al.*, 2018).

The subsurface geoelectric characterization and aquifer type classification show the presence of deep-seated fractures possibly in excess of 117 m in depth extent with percentages of occurrence of

partly weathered/fractured (confined) and fractured (confined) aquifer types of 50% and 6.25% of weathered/fractured (unconfined) aquifer. This shows a significantly high percentage occurrence (56.25%) of partly weathered/fractured basement aquifer which is much higher than the percentage occurrence of the weathered layer aquifer (43.75%). This is a clear indication of the importance of the partly weathered/fractured basement in the assessment of groundwater potential within the Ipogun Drainage Basin.

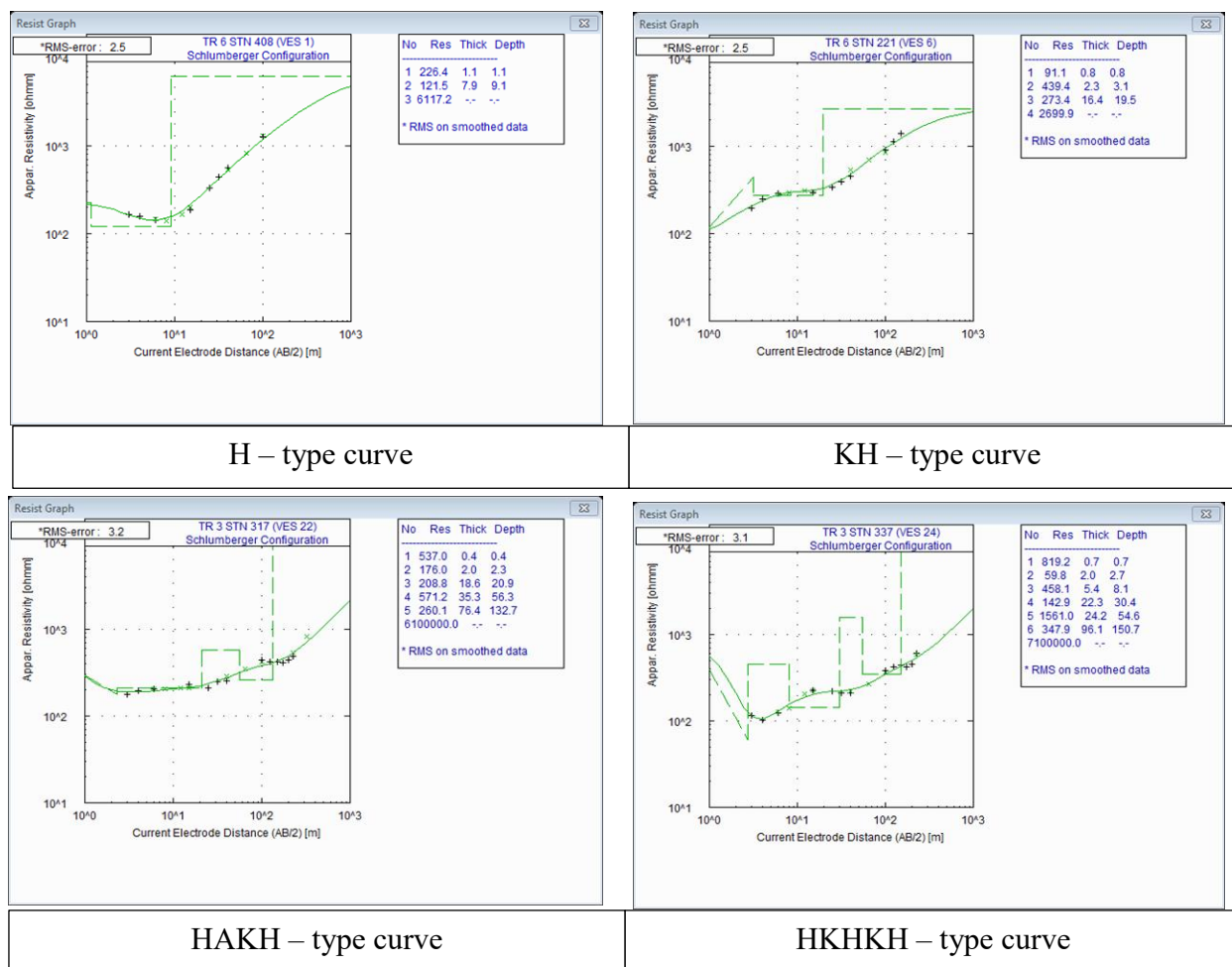


Figure 8: Typical VES type curves obtained from Ipogun drainage basin

Synthesis of Results and Structure Validation

Figures 10 (a-f) correlate magnetic and resistivity anomalous zones with locations of lineaments along traverses TR 1-6. In virtually all cases, the thin/thick dyke magnetic anomalies coincided with 2D low resistivity anomalous zones typical of faults/fractures in a basement terrain (Olorunfemi *et al.* 2020; Bayowa *et al.* 2024). Where the resistivity anomalous zones are relatively close such as along traverses TR 2 (distances 0-200 m); TR 3 (distances 3000-3600 m); TR 4 (distances 2000-2900 m), TR 5 (distances 4000-4500) and TR 6 (distances 2000-2700 m), magnetic anomaly summation (interference) takes place resulting in complex and multiple peak negative magnetic anomalies. This demonstrates the diagnostic characteristics of magnetic anomalies in fault/fracture detection in the basement complex terrain.

Magnetic and remote sensing data were processed for lineaments as reported in Faleye (2021). In this study, twenty-one lineaments code named a-t (Figure 4) were identified along the six traverses (TR 1-6) investigated with seventeen falling within

the 2D dipole-dipole imaging profiles. Fifteen of the referenced 17 lineaments are directly associated with the 2D resistivity anomalous (fault/fractured) zones and are located at or very close to the edges of the resistivity structures. Only two lineaments (b and p) are not such structurally affiliated (Figures 10 a-f). Table 6 contains detailed correlation between lineaments locations and the magnetic and 2D resistivity anomalous zones. The aforementioned shows that lineaments mapped from remotely sensed and geophysical data coincide with edges of linear geologic structures such as fault and fractured zones. The results demonstrate that lineaments extracted from the referenced data are real and of geological and hydrogeological significance.

The 2D resistivity images, geoelectric sections and the 2D magnetic models were also integrated along the traverses with significant correlation in the locations and width extent of the anomalous (fault/fractured) zones (Figures 11 and 12).

Table 4: VES derived subsurface layer geoelectric parameters for Ipogun drainage basin (primary data)

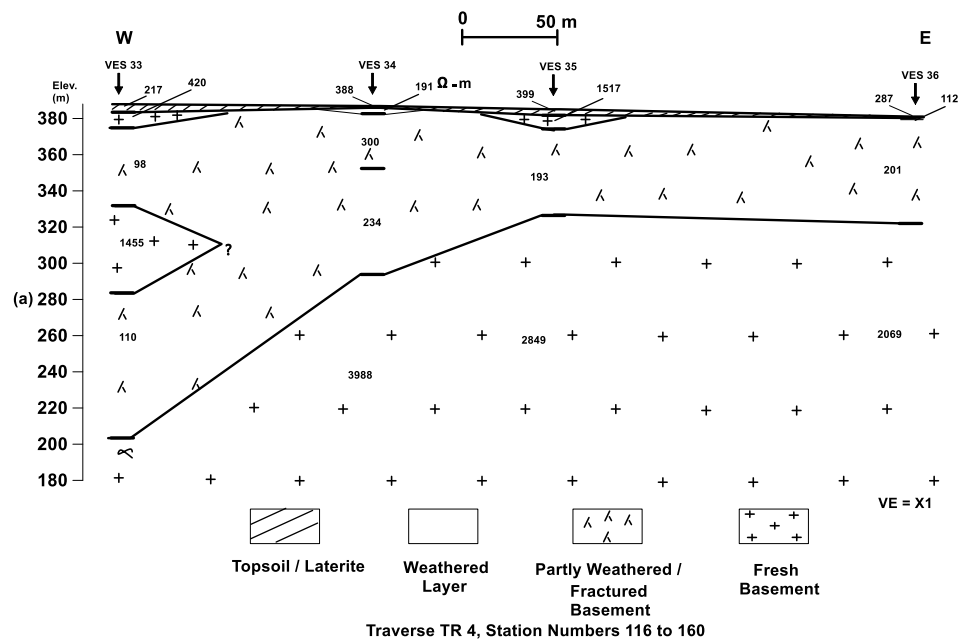
S/N	Lithological Description	Resistivity (ohm-m)		Thickness (m)	
		General Range	Highest Frequency Range	General Range	Highest Frequency Range
1	Topsoil/Laterite	56 – 938	< 400	0.2 – 4.6	< 3.0
2	Weathered Layer	19 – 520	< 150	0.5 – 25.7	< 10
3	Partly Weathered/ Fractured Basement	25 – 1472	< 400	4.5 – 117.2	< 30
4	Fresh Basement	420 - ∞	> 1000	* 0.4 – 185.7	< 20

* Depth to Rock Head (Overburden Thickness)

Table 5: Aquifer type classification and percentage distribution (based on Olorunfemi and Fasuyi, 1993)

Aquifer Type	Type Curve	Frequency	Percentage (%)
Weathered Layer	A,H,HA,KH,QH	21	43.75
Weathered/Fractured (u)	AA,HA	3	6.25
Weathered/ Fractured (c)	AKH,HKH,HAKH,KHKH,HKHKH	16	33.33
Fractured (c)	KH,KHKH	8	16.67
Total		48	100

(u): unconfined; (c): confined



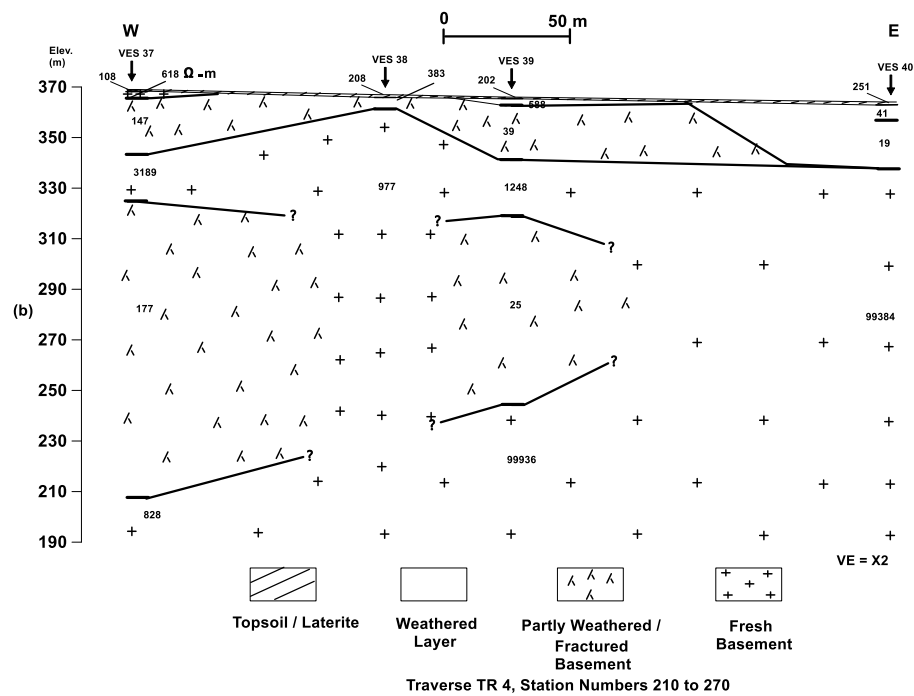


Figure 9: Geoelectric sections along Traverse 4 in W - E direction

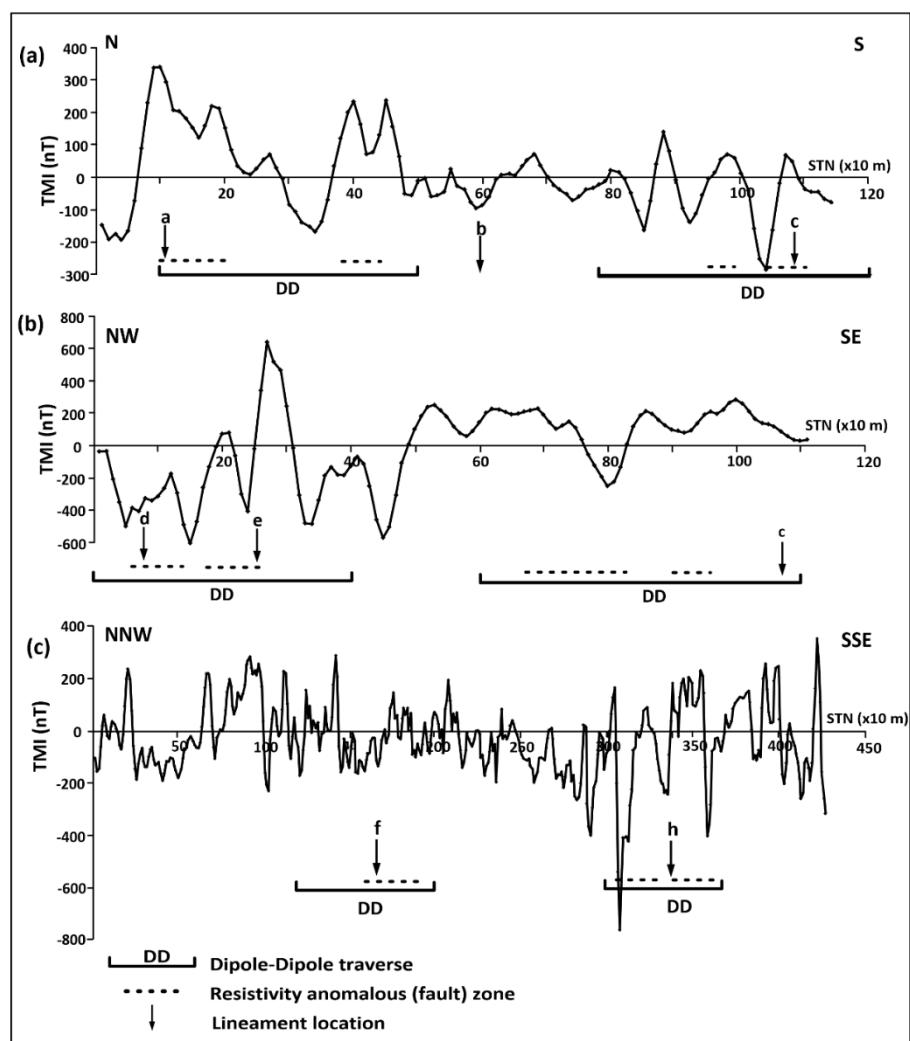


Figure 10: Correlation of lineament, magnetic and resistivity anomalous zones along traverses (a) TR1, (b) TR2 and (c) TR3

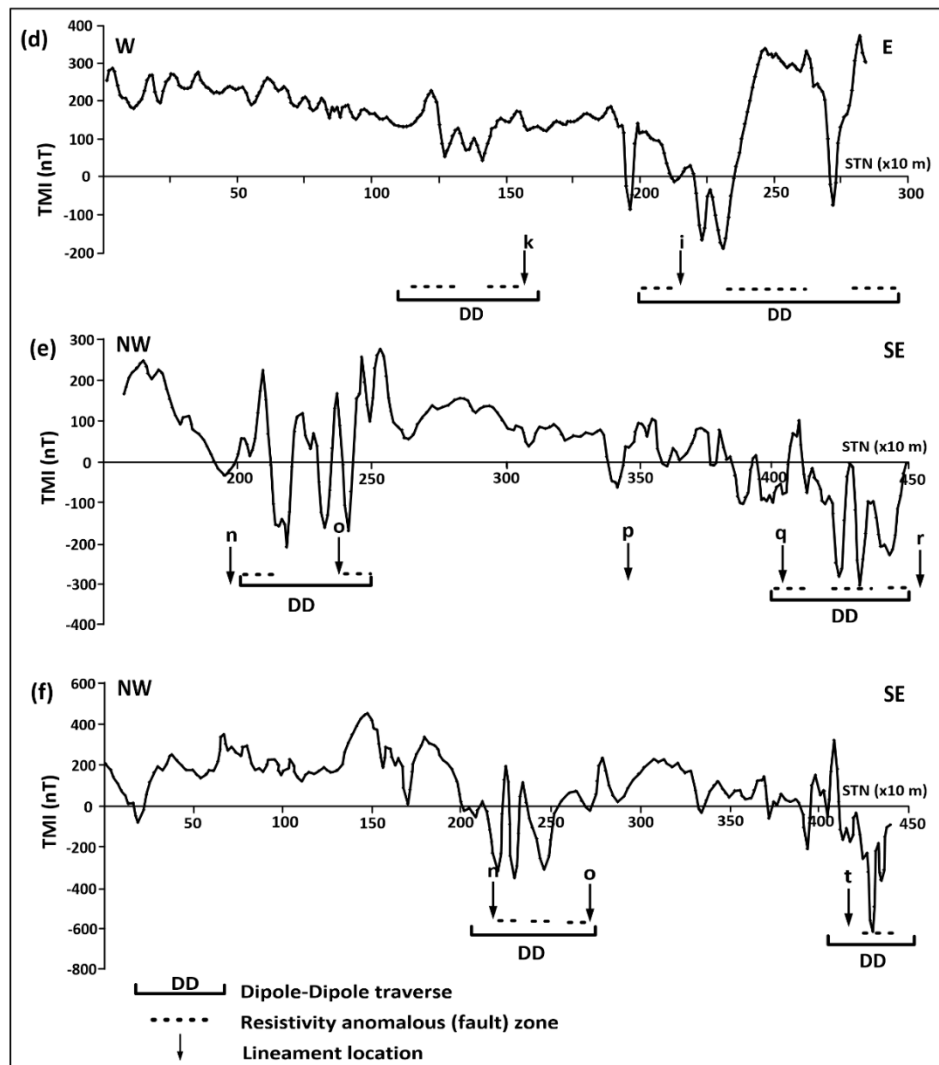


Figure 10: Correlation of lineament, magnetic and resistivity anomalous zones along traverses (d) TR4, (e) TR5 and (f) TR6

Table 6: Correlation of lineaments, magnetic and 2D resistivity anomalous zones

Traverse (TR)	Lineament code	Lineament type	Lineament distance from (Stn. 0) origin (m)	Length of magnetic anomaly/DDI investigated (m)	2D Resistivity anomalous (fault) zone (m)
TR 1	A	Om	120	100-500	120-200; 388-
	B	Om	570	780-1200	440; 940-
	C	Om	1150		980;1040-1100
TR 2	D	Nm	80	0-500	60-120; 170-
	E	Nm	260	600-1100	260; 670-830;
	F	Om	1080		900-960
TR 3	G	Om	360	1200-2000	1560-1640;
	F	Om	1680	3000-3600	3060-3220;
	H	Om	3360		3320-3570
TR 4	I	DEM/Nm	480	1100-1600	114-1300;
	J	Om	720	2000-2860	1420-1570;
	K	DEM	1560		2000-2100;
	L	DEM	2160		2360-2600;
					2780-2860?

TR 5	M	Om	840	2000-2500	2040-2120;
	N	Om	1920	4000-4500	2420-2500;
	O	Om	2400		4000-4140;
	P	Om	3480		4150-4250;
	Q	Om	4080		4280-4340;
	R	Landsat	4560		4380-4470
TR 6	S	Om	4800		
	M	Om	1080	2000-2700	2160-2240;
	N	Om	2160	4000-4500	2320-2460;
	O	Om	2640		2580-2660;
	P	Om	3480		4260-4360;
	T	DEM	4080		
	Q	Om	4560		

Om: Overlapping magnetic lineaments; Nm: Non-Overlapping magnetic lineament; DEM: Digital Elevation Model lineaments; Landsat: Landsat Imageries lineament DDL: Dipole-Dipole Line; Stn: Station.

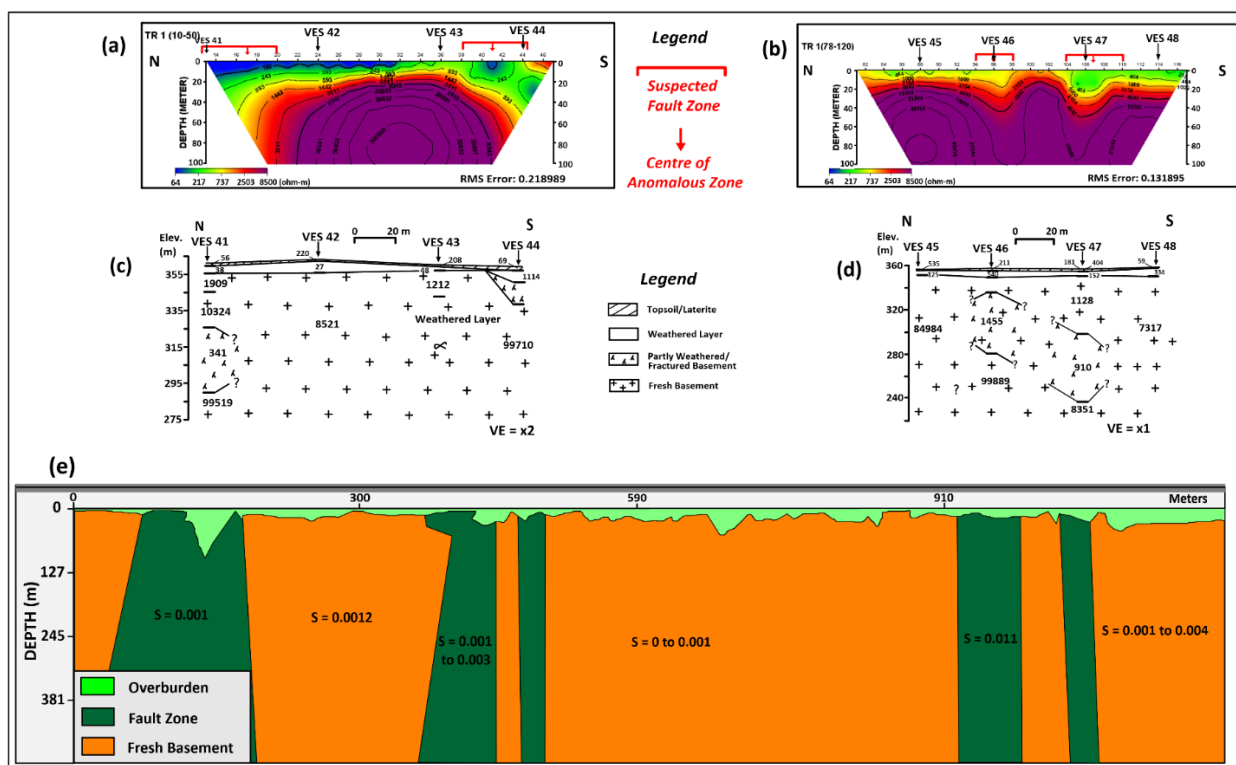


Figure 11: Correlated (a & b) 2D resistivity structures (c & d) geoelectric sections and (e) 2D magnetic model along Traverse 1

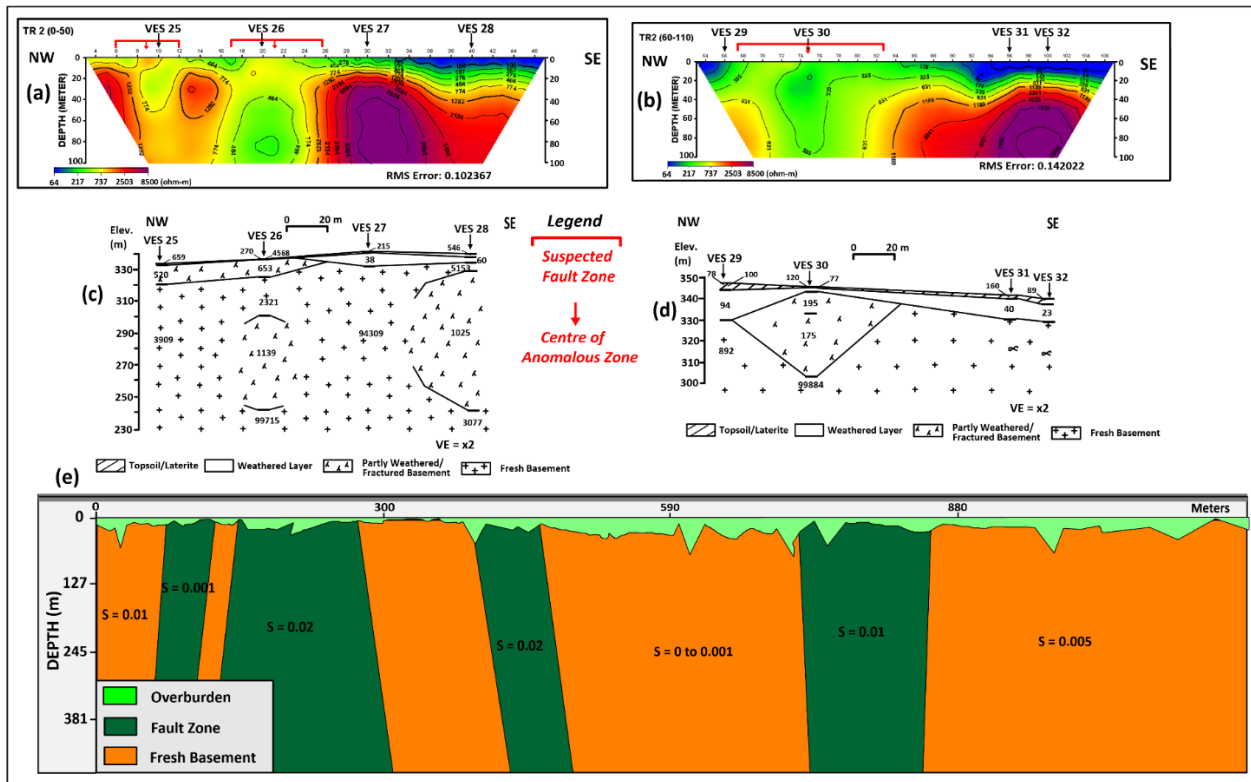


Figure 12: Correlated (a & b) 2D resistivity structures (c & d) geoelectric sections and (e) 2D magnetic model along Traverse 2

Groundwater Potential Assessment

The thickness of the weathered layer aquifer within the study area varies from 0.5 to 25.7 m (but generally < 10 m) and hence relatively thin. The aquifer resistivity is generally low (< 150 ohm-m) due to its clayey nature with tendency for low permeability and low groundwater yielding capacity. Large number of the existing boreholes within the investigated basin were terminated at relatively shallow depths (< 40 m) and within the low groundwater yielding weathered layer aquifer. This may account for the generally low groundwater yields (< 1.0 l/s) of the boreholes drilled within the basin.

However, based on the results from the current study, the weathered layer aquifer accounts for 43.8% of the delineated aquifer types (Table 5). The study also established a partly weathered/fractured basement aquifer with a generally moderate (< 400 ohm-m) resistivity that occurs slightly more frequently (56.2%) than the weathered layer aquifer. This aquifer unit has thicknesses that range from 4.5-117 m and width extent of 20-255 m with moderate to high storage capacity, higher permeability, enhanced

groundwater yielding capacity and prospect for higher groundwater potential.

A domestic borehole was drilled at the edge of a fault-indicating low resistivity structure and in the premises of lineament h (Figure 4) along traverse TR 3 (300-360) (Figure 13a) with depth extent exceeding 100 m on the 2D resistivity image. The 60 m deep borehole penetrated a thin (9.4 m) weathered layer aquifer (with no hydrogeological significance) and a 21.6 m confined fractured basement aquifer (Figure 13b) was terminated within the fractured basement with an enhanced groundwater yield of 1.4 l/s. The borehole yield could have been more were it to harness the entire delineated fractured basement column with a deeper optimum depth.

CONCLUSION

This study engaged ground magnetic profiling, 2D resistivity imaging and 1D VES techniques to assess the groundwater potential of the Ipogun Drainage Basin. Twenty-one lineaments were identified along the investigated traverses with 17 of them located within the 2D resistivity imaging lines. Fifteen of the referenced 17 lineaments were found to be directly associated with low resistivity

discontinuous zones (typical of water bearing faulted/fractured basement (Olorunfemi *et al.*, 2021) on the 2D resistivity images and are situated at or very close to the edges of the resistivity structures. This shows that the delineated lineaments are real geological features with hydrogeological significance.

The lineaments related to 2D resistivity-delineated-suspected faulted/fractured basement

zones have width extent of 40-250 m and depth extent of 20 to > 100 m at several locations. These results are corroborated by the width extent of 20-255 m established from magnetic modelling and the 1D VES estimated thicknesses of between 4.5 and 117.2 m. The above demonstrates a moderate to large faulted/fractured basement aquifer storativity.

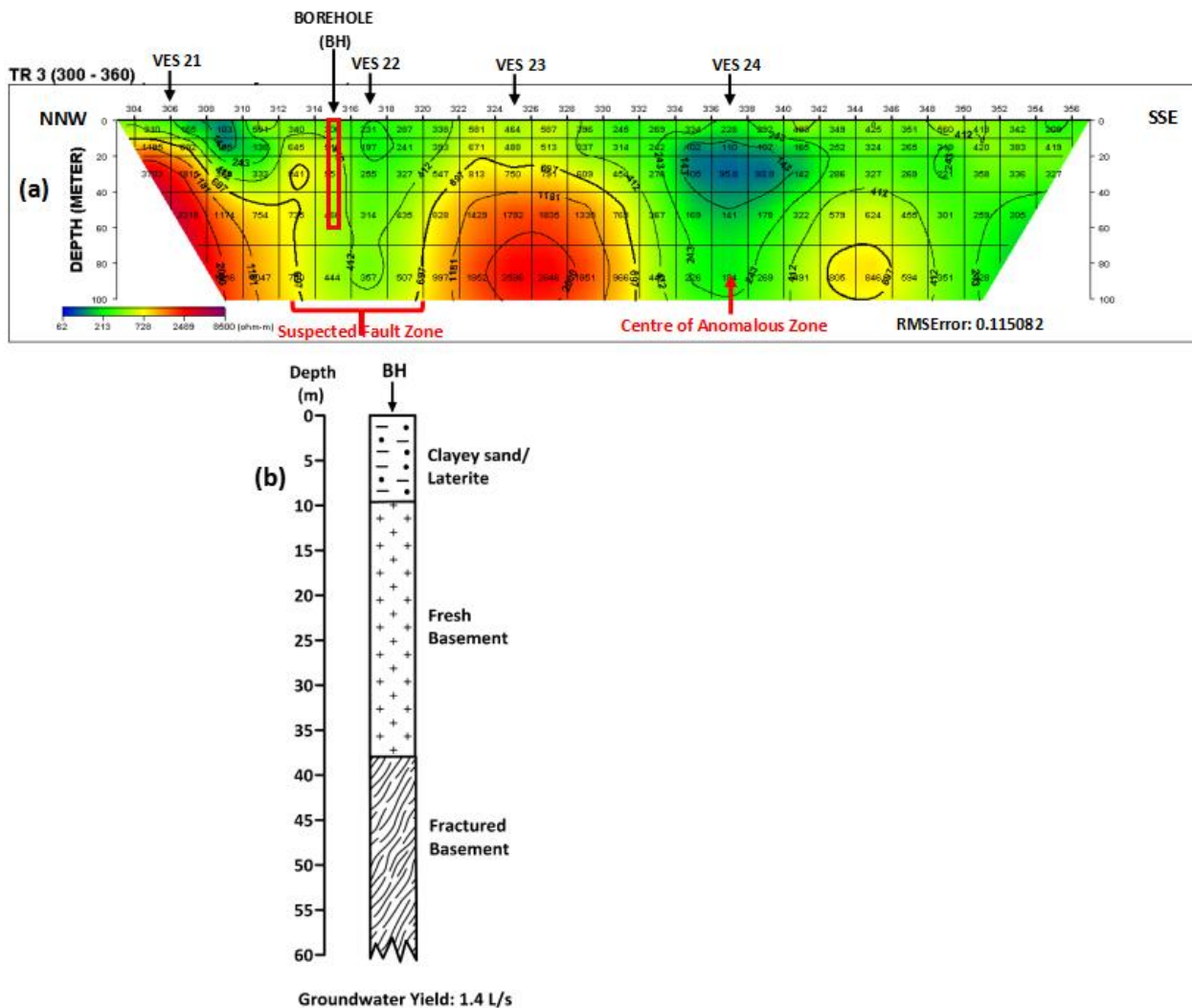


Figure 13: (a) Parametric 2D resistivity image to a borehole site and (b) lithological log of the borehole

The resistivity of the partly weathered/fractured basement is 61-1714 ohm-m (but are generally < 1000 ohm-m) from 2D resistivity images and 25-1472 ohm-m with a highest frequency of < 400 ohm-m from VES. This shows a generally moderate resistivity values which could be indicative of a relatively high density of fracturing and moderate clay content with tendency for high aquifer transmissivity. These geophysical-hydrogeological parameters are reflective of the potential of the faulted/fractured aquifer to store

and transmit groundwater, thereby enhancing the groundwater potential.

The results of this study corroborate the relatively thin (generally < 20 m) and clayey weathered layer aquifer (with resistivity of generally < 150 ohm-m from recent study and previous audit report) with consequently low groundwater yield and potential (Faleye 2021). However, in the present study, the partly weathered/fractured basement (equivalent of the fault/fracture zone) has a slightly higher

frequency of occurrence (56.2%) than the weathered layer aquifer (with 43.8% occurrence). This is a demonstration of the significance of the partly weathered/fractured aquifer in the assessment of the groundwater potential of the Ipogun Drainage Basin. An enhanced groundwater yield of 1.4 l/s was obtained from a borehole drilled through a weathered layer and confined fractured basement aquifers to a depth of 60 m, without fully harnessing the entirety of the fractured basement aquifer.

It is can therefore be concluded that the basin has prospect for high groundwater potential, in areas where the basement is weathered and fractured to deep depth, and the fractures are interconnected over a large area, to influence transmission and storativity of the groundwater. Drilled depths could be in excess of 100 m as against the previous reliance on relatively shallow subsurface.

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AUTHOR CONTRIBUTIONS

All authors contributed to the study. Data acquisition, analysis and writing of first draft of the manuscript: [E.T.F.]; Supervision, review and editing: [M.O.O.]; Data analysis: [A.S.A.]; Data acquisition and analysis: [O.E.B.]; Data analysis and review: [A.G.O.]. All authors approved the final manuscript.

DISCLOSURE STATEMENT

The authors declare that there is no conflict of interest.

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