https://dx.doi.org/10.4314/dujopas.v10i2a.14
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 10 No. 2a June 2024*

Assessing the Challenges of Viability of Borehole Through the Extraction of Lineaments from Aeromagnetic Data Within a Hostel at Air Force Institute of Technology, Kaduna, Nigeria

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Abstract

The study area has received little attention from scholars due to being within a military facility. The Institute is relatively young, thus undergoing development including but not limited to providing portable water supply. However, boreholes are the primary source of water supply. Four of the nine boreholes sunk within the hostel failed and there's no published work looking into the potential reason for the failure. The aeromagnetic data of the study area were subjected to an edge-detecting technique, the second vertical derivative, to reveal lineaments within the study area. The lineaments represent structures like faults, fractures, and other features that could act as secondary porosity in the aquifer. Moreover, the Euler depth technique was also applied to determine the possible depth of the lineament. A NE trending lineament was mapped around the boreholes within the hostel. The depth of the lineaments around boreholes is about 300 m deep suggesting the area may not be viable for sinking a borehole, the cost of drilling to that depth will be huge.

Keywords: aeromagnetic data, lineament, underground water, AFIT, Euler deconvolution.

INTRODUCTION

Groundwater accessibility is pivotal for sustaining daily activities within any community (Carrard *et al*., 2019; Velis *et al*., 2017), and boreholes serve as essential sources of this invaluable resource. Nevertheless, the precise formation processes of the groundwater reservoirs are not well comprehended due to insufficient comprehensive data (Akintayo et al., 2022). The permeability and storage capacity of the groundwater system in the Basement complex are closely tied to structural attributes, such as the arrangement and scale of fractures, as well as the depth and degree of weathering (Clark L., 1985; Eduvie M, 1998).

However, the success and reliability of boreholes can be significantly impacted by geological factors, notably the presence of lineaments— linear geological structures, such as fractures and faults (Bon *et al*., 2022; Tam *et al*., 2004). These lineaments can dictate the movement and storage of groundwater, directly influencing the effectiveness of boreholes (Boitt *et al*., 2023; Nyaberi *et al*., 2019).

The subsurface geological framework surrounding groundwater potential is a network of complex structures, encompassing faults, fractures, and other lineaments. These features represent geological discontinuities that significantly influence groundwater flow and storage (De Vargas *et al*., 2022; Park *et al*., 2000). The complex interplay among these subsurface structures often leads to borehole failures, presenting a critical challenge in ensuring a sustainable water supply for community spaces (Akingboye & Osazuwa, 2021; De Vargas *et al*., 2022; Olorunfemi & Oni, 2019).
Understanding these lineaments is pivotal for deciphering the underlying geological complexities that impede borehole functionality (Mabee *et al*., 2002). Advanced geophysical methods, such as aeromagnetic surveys, stand at the forefront of unraveling these complexities. They offer a nuanced perspective, allowing us to peek beneath the Earth's surface and visualize the invisible network of subsurface structures (Ijeh *et al*., 2018; Ishola *et al*., 2020).

Lineaments, when accurately identified and characterized, unveil a wealth of information about the geological composition and behavior of the subsurface (Prabu & Rajagopal, 2013; Takorabt *et al*., 2018). They serve as indicators of potential areas of stress, zones of increased permeability, or impediments to groundwater flow (Mpofu *et al*., 2020; Sarwar *et al*., 2021). By comprehending these lineaments through advanced geophysical methods, we gain invaluable insights into the fundamental geological processes governing borehole performance (Day-Lewis *et al*., 2017; Ejepu *et al*., 2017; Wiederhold *et al*., 2021).

Moreover, these insights transcend mere identification; they offer a predictive capability crucial for borehole siting and maintenance (Falebita *et al*., 2020; Khan *et al*., 2023). By discerning the orientation, distribution, and characteristics of lineaments, we can anticipate potential challenges in borehole construction and operation (Mangs *et al*., 2023; Ouattara *et al*., 2021). This foresight allows for proactive measures, mitigating risks associated with borehole failures and optimizing the reliability of water supply in community spaces.

The utilization of advanced geophysical methods to unravel the enigmatic nature of subsurface lineaments represents a leap forward in understanding and managing groundwater potentials(Ishola *et al*., 2023; Mohamed *et al*., 2023; Wiederhold *et al*., 2021). Aeromagnetic data gathered through high-resolution aerial surveys, offers a unique opportunity to investigate subsurface variations in magnetic properties. By leveraging this data and employing techniques such as the first vertical derivative, we aim to enhance the identification of subtle magnetic anomalies associated with subsurface geological structures, including lineaments. Additionally, the application of Euler deconvolution, a mathematical method for estimating the depth and location of magnetic sources, will be employed to refine the identification and characterization of lineaments (Ilugbo & Adebiyi, 2017; Keating & Pilkington, 2004; Mohamed *et al*., 2023; Tawey *et al*., 2019). The geophysical techniques (the first vertical derivative, and Euler deconvolution) present a comprehensive methodology to comprehend the relationship between subsurface structures and groundwater potentials within the hostel, which hitherto is lacking.

This paper aims to outline the methodology employed in utilizing aeromagnetic data, first vertical derivative analysis, and Euler deconvolution for delineating lineaments around boreholes within the hostel premises. Through this investigation, we seek to shed light on the geological factors impacting borehole performance and offer valuable insights for enhancing water resource management strategies within community environments.

The study area

The male hostel at AFIT lies within latitude 10.626° N – 10.617° N and 7.453° E – 7.435° E. In the vicinity of the hostel, there are five operational boreholes alongside four non-functional ones. The study area falls within the Igabi Local Government Area, Kaduna State, Nigeria, which holds substantial untapped groundwater reservoirs vital for sustainable progress. In this location, the occurrence of groundwater is mainly associated with three separate geological formations: the River Alluvium, the Newer Basalts, and the Weathered/Fractured Basement Complex (Alaminiokuma & Chaanda, 2020).

The research area is mostly covered by the Precambrian rocks of the Nigerian Basement Complex, which is known for its crystalline structure (see Figure 1). The weathering of these rocks in tropical climates produces a wide range of unconsolidated materials, with considerable differences in both thickness and horizontal spread (Dearmaun *et al*., 1978). The rocks of the Basement Complex are predominantly composed of migmatite gneiss, metasediments/metavolcanic formations (such as schist, quartzite, amphibolites, and banded iron formations), pan-African granitoids, calc-alkaline granites, and volcanics from the Jurassic period (McCurry, 1976). Over time, these rock formations, especially the gneisses and schists, have experienced numerous instances of orogenic activity, resulting in significant deformation and metamorphosis.

Moreover, the area also contains a variety of rock types like quartz veins, pegmatite, and xenoliths. The earliest rocks in the vicinity are gneisses and older metasediments, originating from the Birrimian period around 2500 million years ago (McCurry, 1975). Although primarily made up of igneous and metamorphic rocks, the Nigerian Basement Complex has been wrongly labeled as an inadequate aquifer (Egboka, 1988; Hazell *et al.*, 1992). This thermotectonic occurrence has largely erased previous geological marks but has resulted in recognizable structural characteristics, including folding, fracturing, shearing, granitic intrusions, and granitization. The Migmatite-Gneiss Complex underlying a significant portion of the Kaduna-Zaria region, stands out notably for its clear display of migmatite formations in areas like Kudenda, Kakau, Sabon Tasha, and Kabala, situated both to the east and west of the Kaduna metropolis (Offodile, 1992).

The study area's structural characteristics include joints, foliation, micro-folds, faults, veins, and foliation (Garba *et al*., 2018). The orogeny Pan-African, around 500 million years ago and left most rocks with a predominate northeast-to-southwest trend direction, is thought to be responsible for many of these features (Egba, 2013). Through thorough geological mapping of the area, pegmatitic veins are sporadically found in the northeastern region near Mando, maybe extending to AFIT. The two main types of rocks in the region are Biotite-Granite and Migmatite-Gneiss. It is well known that these rock formations create aquitards and permeable zones in the local bedrock, which affect the dynamics of groundwater flow. Furthermore, the crystalline rocks of the basement complex contain fractures, fissures, veins, joints, and other structural deformations that greatly regulate groundwater flow and impact the principal aquifer units' rates of recharge and discharge (Ogezi, 1998).

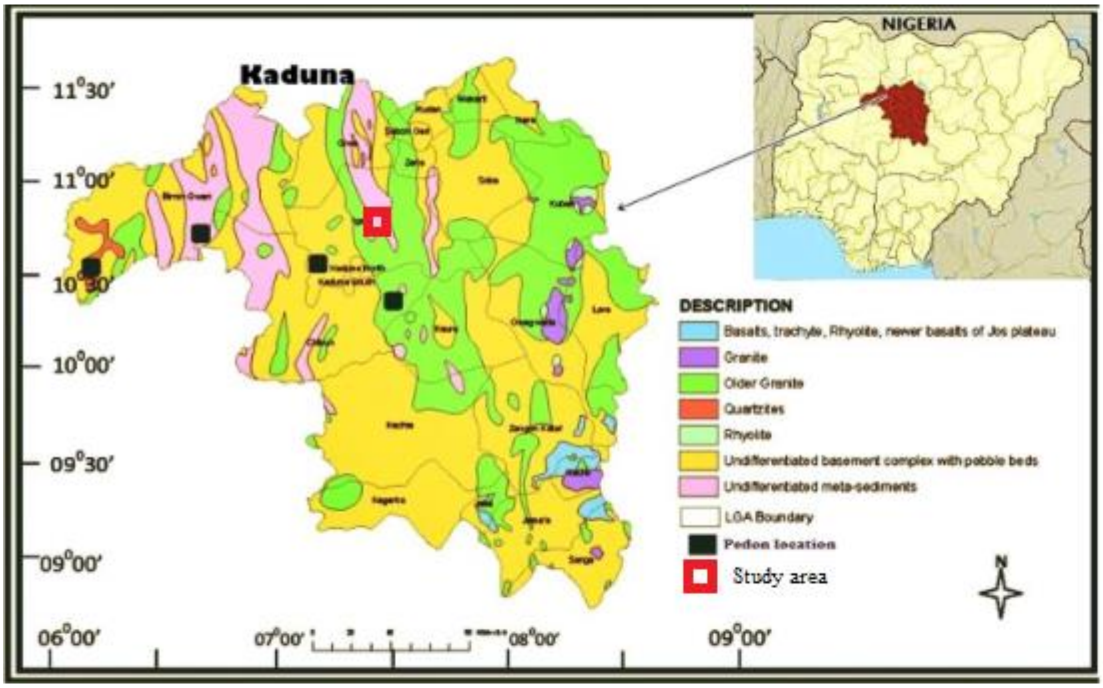

Figure 1: Geologic map of Kaduna. Modified after Sadiq *et al.* (2021).

MATERIAL AND METHODS

The aeromagnetic data covering latitude 10°15ˈN - 10°45ˈN and longitude 7°15ˈE – 7°45ˈE used for this research was obtained from the Nigerian Geological Survey Agency (NGSA) Abuja. According to NGSA website, funding for the survey came from the World Bank and the Federal Government of Nigeria, and it was conducted between 2005 and 2009. It was completed in two stages: the World Bank and the Nigerian government jointly backed Phase 2, while the Nigerian government alone funded Phase 1. Fugro Airborne Surveys was in charge of gathering, handling, and analyzing the airborne geophysical data.

The methods involved in this study include:

1. Create the study area's Total Magnetic Intensity (TMI) map using Oasis Montaj software
2. Application of the Second Vertical Derivative to manually map out the structures
3. Produce a map of Euler deconvolution for magnetic source bodies' structures and depth.

Total magnetic intensity

The X column of the airborne magnetic data denotes longitude/easting, the Y column denotes latitude/northing, and the Z column denotes the overall magnetic intensity in the data that was acquired from Fugro. The Total Magnetic Field Intensity data (Z) were first corrected by deducting 33,000 nT to simplify processing. After obtaining the data from NGSA, the original Total Magnetic Field Intensity values were restored by performing a straightforward arithmetic addition of 33,000 nT to each Z column value. Only then could further processing be carried out. The Universal Transverse Mercator (UTM) projection system was then used to georeference the X and Y columns, designating them as the preferred columns Finally, the data was gridded to generate the total magnetic intensity (TMI) grid map as shown in Figure 2 below.

The interpretation of magnetic anomalies reported in low- and moderate-latitude locations is frequently complicated by their polarity. The magnetization vector and the induced magnetic field vector's inclination both affect this polarity (Yaoguo and Douglas, 2001). Repositioning magnetic anomalies above their causal sources is what Baranov (1957) called the reduction to the Pole (RTP) transformation approach, which aims to solve this problem.

On the other hand, along the magnetic declination direction, the RTP operator becomes unbounded as magnetic latitude approaches the equator, which causes an amplification of noise in this direction. As a result, linear characteristics that are aligned with the direction of declination dominate the resulting RTP field. The pattern of induced magnetic anomalies becomes extremely dependent on their orientation, which is further complicated by the presence of a horizontal inductive field close to the equator. Large anomalies, for example, can be produced by east-west oriented bodies, but lengthy north-south oriented bodies, despite having significant magnetic susceptibility, can look nearly invisible magnetically.

The Reduce-to-Equator (RTE) filter is commonly applied to total magnetic intensity data to overcome these difficulties. This filter mimics anomaly magnitudes as they would look near the equator by transforming the data into an equatorial pattern. Accurate interpretation is made possible by the RTE filter's stability, which guarantees that the filtered result stays undistorted. As a result, the source magnetic field and the regional magnetic field both become horizontal, allowing for a clearer examination. However, Nigeria is so close to the equator, there is no need for the filtration procedure. Instead, to reduce the impact of the regional field on the local sources, a regional-residual separation is needed.

Second vertical derivative

According to Foss (2011), vertical derivative filters attenuate longer wavelengths while enhancing short-wavelength components of the magnetic field. These filters, which are usually applied to gridded data using FFT (Fast Fourier Transform) filters, scale the field's amplitude spectra by a certain factor to compute various vertical derivatives of the magnetic field:

$$\frac{1}{n}\left[(U^2+V^2)^{\frac{1}{2}}\right]^n \qquad 1$$

The amplitude spectra of the magnetic field are multiplied by a factor involving the wavenumbers (U, V) corresponding to the (x, y) directions, respectively, to obtain the order of the vertical derivative, represented by n. Comparable to concurrently measuring the magnetic field at two points vertically above one another, subtracting the data, and dividing the outcome by the vertical spatial separation between the measurement locations is the second vertical derivative operation. Sharper edges are produced by using this method to improve the resolution of anomalies and shallow features. The data is then manually mapped to locate and define structures.

Euler Deconvolution

The two main goals of many processing algorithms for magnetic data analysis are boundary delineation and depth estimation. However, according to Reid *et al*. (1990), Euler deconvolution functions as a border and depth estimator as well. It functions by taking data out of grids using Thompson's (1982) homogeneity relationship. This relationship can be expressed in the following manner:

$$(x-x_0)\frac{\delta T}{\delta x}(y-y_0)\frac{\delta T}{\delta y}+(z-z_0)\frac{\delta T}{\delta z}=N(B-T) \qquad 2$$

where the location of a magnetic source whose total field T is observed at (x, y, z) is denoted by (x_0, y_0, z_0). N is the degree of homogeneity, which is understood as the structural index (SI) (Thompson, 1982). This structural index was selected based on past knowledge of the

source geometry and represents the rate of change at field distance. B is the regional field value.
According to Reid et al. (1990), the structural index (SI) for different bodies (N= 0 for contacts, 1 for sills, dykes, and faults, 2 for pipes and horizontal bodies, and 3 for spherical bodies) varies from zero (0) to three (3).

RESULTS AND DISCUSSION
The gridded TMI is shown in Figure 2, indicating several linear structures around the study area. The major trend of the structures is in the NW direction. They are pronounced in the northeast and southwest regions. Some were trending in the E-W direction, observed in the central region of the study area. The borehole within the male hostel at AFIT lies on the path of an NE-trending anomaly.

The region of interest was zoomed out to reveal subtle features. Regional-residual separation filtering was carried out on the aeromagnetic data of the region of interest. Subsequently, the residual magnetic data was subjected to second vertical derivatives which usually sharpen the edges of linear features (Figure 3). The NE trending lineament that manifests on the TMI map is pronounced in the map of the second vertical derivative, it is regional in nature (Goki *et al.,* 2011).

The direction and depth of the linear features within the region of interest were revealed with the application of Euler deconvolution on the aeromagnetic data of the region of interest (Figure 4). The depth of the NE trending lineament around the wells is about 300m deep. This suggests that boreholes drilled beyond the depth are likely to be viable. However, drilling to that depth will be very expensive. Four out of nine boreholes drilled within the hostels that have failed could be within the region where conduits for the transport of underground water are lacking. Moreover, it is possible they were drilled to a depth less than the depth of the identified lineament within the study area.

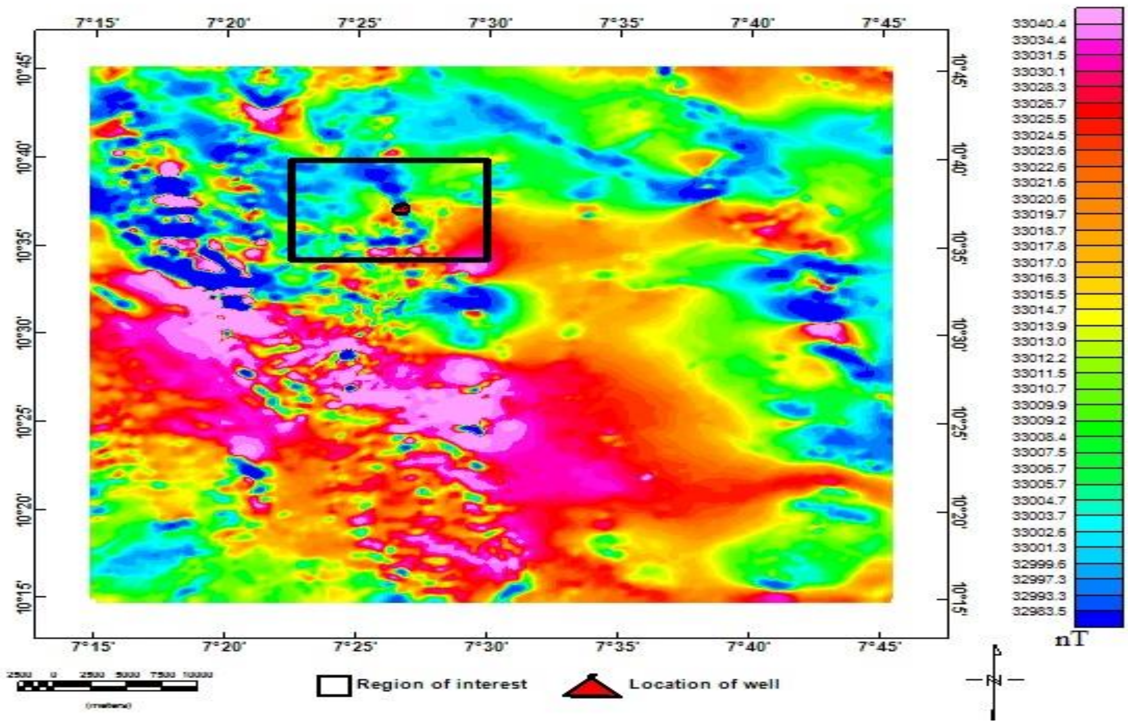

Figure 2: Total magnetic intensity of the study area

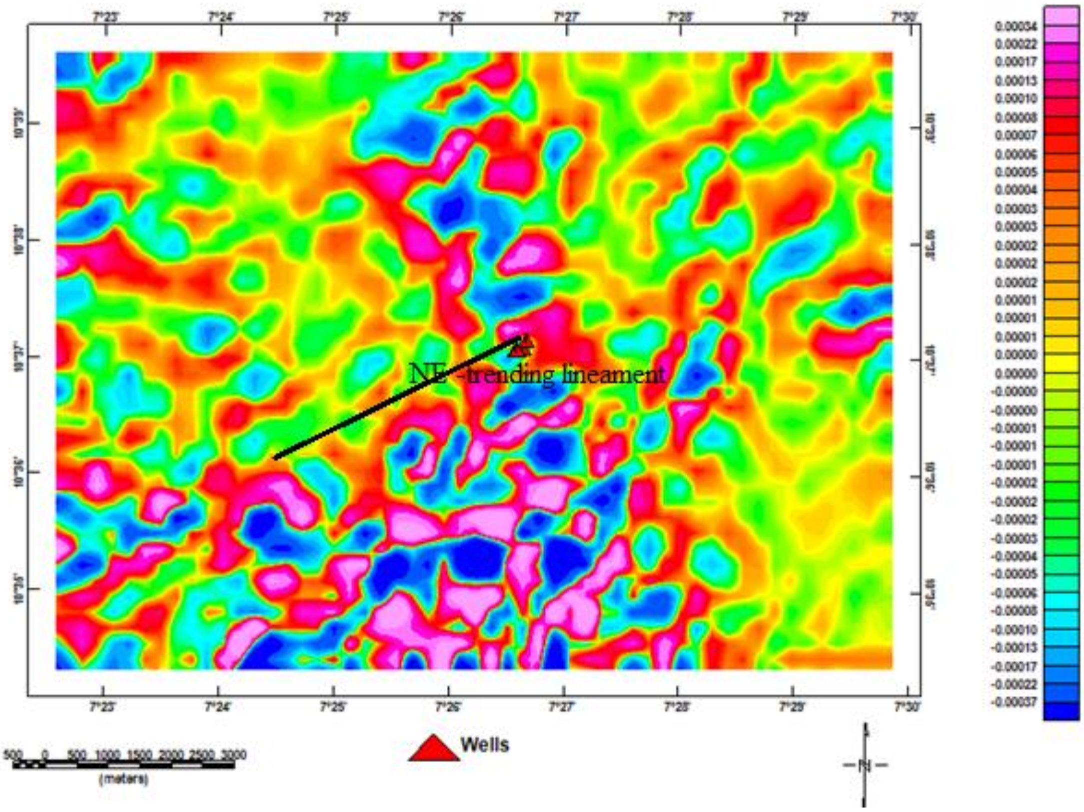

Figure 3: Second vertical derivative map of the region of interest

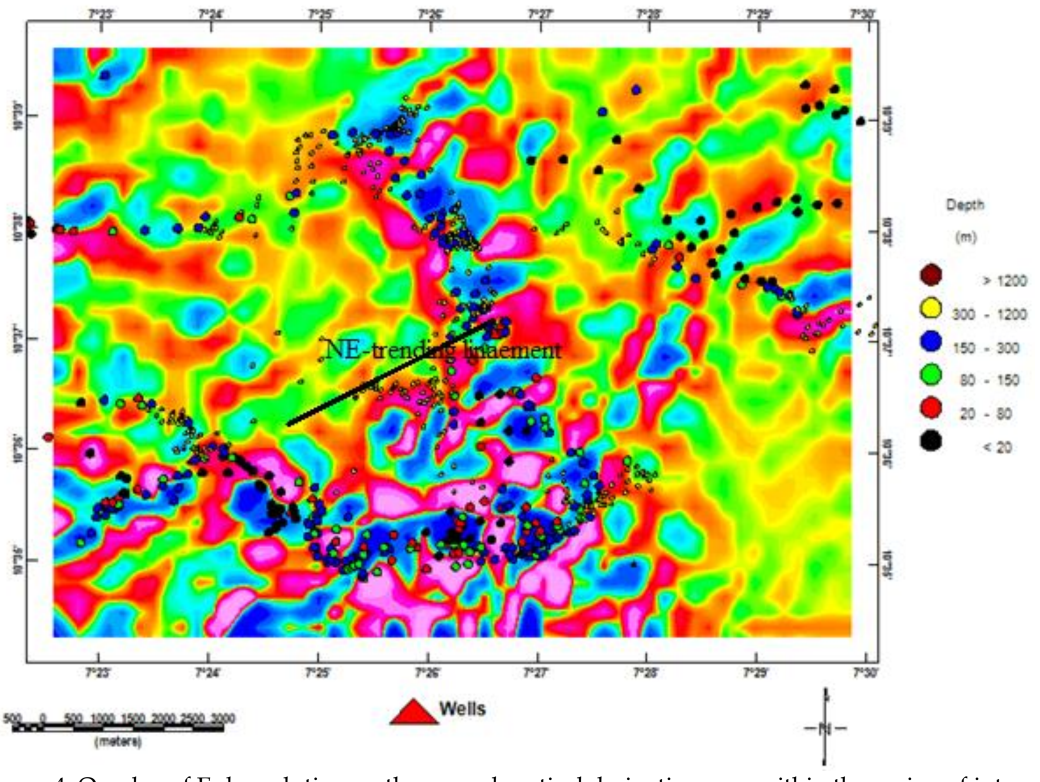

Figure 4: Overlay of Euler solution on the second vertical derivative map within the region of interest

CONCLUSION

The study area has received little attention from scholars due to being within a military facility. The Institute is relatively new, and undergoing development including but not limited to portable water supply. However, boreholes are the primary source of water supply. Four of the nine boreholes sunk within the hostel failed and there's no published work investigating the possible cause of the failure within the study area, to the best of the knowledge of the author.

The aeromagnetic data of the study area were subjected to the edge-detecting technique, second vertical derivative, to reveal lineaments within the study area. The lineaments represent structures like faults, fractures, and other features that could act as channels for transporting underground aquifer water.

Moreover, the Euler depth technique was also applied to determine the possible depth of the lineament. A NE-trending lineament was mapped around the boreholes within the hostel. The depth of the lineaments around boreholes is about 300 m deep suggesting the area may not be viable for sinking a shallow productive boreholes. Other geophysical techniques, e.g. resistivity method, could be adopted to investigate a viable location for sinking a productive borehole.

REFERENCES

Akingboye, A. S., & Osazuwa, I. B. (2021). Subsurface geological, hydrogeophysical and engineering characterisation of Etioro-Akoko, southwestern Nigeria, using electrical resistivity tomography. *NRIAG Journal of Astronomy and Geophysics*, *10*(1), 43–57. https://doi.org/10.1080/20909977.2020.1868659

Akintayo, T., Bello, S. A., Ugwu, S. J., & Mwali, C. N. (2022). Determination of groundwater potential areas in Kaduna metropolis, Kaduna, Nigeria. *FUDMA JOURNAL OF SCIENCES*, *5*(4), 194–204. https://doi.org/10.33003/fjs-2021-0504-806

Alaminiokuma, G. I., & Chaanda, M. S. (2020). Groundwater Potential of Mando, Kaduna, Crystalline Basement Complex, Nigeria. In *Journal of Earth Sciences and Geotechnical Engineering* (Vol. 10, Issue 2). online) Scientific Press International Limited.

Boitt, M., Khayasi, P., & Wambua, C. (2023). Assessment of Groundwater Potential and Prediction of the Potential Trend up to 2042 Using GIS-Based Model and Remote Sensing Techniques for Kiambu County. *International Journal of Geosciences*, *14*(10), 1036–1063. https://doi.org/10.4236/ijg.2023.1410053

Bon, A. F., Ombolo, A., Biboum, P. M., Moutlen, J. M., & Mboudou, G. E. (2022). Identification of hydrogeological features using remote sensing and electromagnetic methods in the hard- rock formations of the Cameroon coastal plain (Central Africa): implications for water borehole location. *Scientific African*, *17*, e01272. https://doi.org/10.1016/j.sciaf.2022.e01272

Carrard, N., Foster, T., & Willetts, J. (2019). Groundwater as a Source of Drinking Water in Southeast Asia and the Pacific: A Multi-Country Review of Current Reliance and Resource Concerns. *Water*, *11*(8), 1605. https://doi.org/10.3390/w11081605

Clark L . (1985). Groundwater Abstraction From the Basement Complex Areas of Africa. . *Quarterly Journal for Engineering Geology, London*, *18*, 25–34.

Day-Lewis, F. D., Slater, L. D., Robinson, J., Johnson, C. D., Terry, N., & Werkema, D. (2017). An overview of geophysical technologies appropriate for characterization and monitoring at fractured-rock sites. *Journal of Environmental Management*, *204*, 709–720. https://doi.org/10.1016/j.jenvman.2017.04.033

De Vargas, T., Boff, F. E., Belladona, R., Faccioni, L. F., Reginato, P. A. R., & Carlos, F. S. (2022). Influence of geological discontinuities on the groundwater flow of the Serra Geral Fractured Aquifer System. *Groundwater for Sustainable Development*, *18*, 100780. https://doi.org/10.1016/j.gsd.2022.100780

Dearmaun, W., Dayness, F., & Irfar, T. (1978). Engineering Grading of Weathered Granite. . . *Engineering Geology Granite*, *12*, 345-374.

Eduvie M. (1998). *Groundwater Assesment and Borehole Characteristics: Case Study of Kaduna Metropolis.* .

Egba, M. C. (2013). *The Geology of Dumbi part of Igabi Local Government Area Kaduna State*. Ahmadu Bello University Zaria.

Egboka, B. (1988). The Hydrogeological Provinces of Nigeria . *Water Quality Bulletin*, *13*(4), 117-125.

Ejepu, J., Olasehinde, P., Okhimamhe, A., & Okunlola, I. (2017). Investigation of Hydrogeological Structures of Paiko Region, North-Central Nigeria Using Integrated Geophysical and Remote Sensing Techniques. *Geosciences*, *7*(4), 122. https://doi.org/10.3390/geosciences7040122

Falebita, D., Olajuyigbe, O., Sunday Abeiya, S., Christopher, O., & Aderoju, A. (2020). Interpretation of geophysical and GIS-based remote sensing data for sustainable groundwater resource management in the basement of north-eastern Osun State, Nigeria. *SN Applied Sciences*, *2*(9), 1608. https://doi.org/10.1007/s42452-020-03366-x

Garba, H., Norman, S., & Bayang, F. (2018). Modelling the Transmissivity of an Aquifer Using Laboratory Tests and Vertical Electrical Sounding in Igabi Lga Kaduna State. *International Journal of Science and Research*. https://doi.org/10.21275/ART20203089

Goki, N.G., Amadi, A.N., Olasehinde, P.I., Dada S.S., Ikpokonte, E.A., and Adekeye, J. I. D. (2011). Appraising the structural geology of Kakuri Sheet 144: Implications for the tectonic evolution of the basement complex. *Journal of Engineering and Technology Research*, (2); 26 – 36.

Hazell, J. I. D., Cratchley, J. R. T., and Jones, C. R. (1992). The Hydrogeology of Crystalline Aquifers in Northern Nigeria and Geophysical Techniques used in their Exploration . In *A Publication of Geological Society Publication* (Vol. 66). Wright, E.P. and Burges, W.G.

Ijeh, B. I., Ohaegbuchu, H. E., & Okpetue, P. C. (2018). Integration of Aeromagnetic Data and Landsat Imagery for Structural Analysis: A Case Study of Awgu in Enugu State, South-Eastern, Nigeria. *World News of Natural Science*, *18*(2), 79–105. www.worldnewsnaturalsciences.com

Ilugbo, S. O., & Adebiyi, A. D. (2017). Intersection of lineaments for groundwater prospect analysis using satellite remotely sensed and aeromagnetic dataset around Ibodi, Southwestern Nigeria. *International Journal of Physical Sciences*, *12*(23), 329–353. https://doi.org/10.5897/IJPS2017.4692

Ishola, K. S., Akerele, P. O., Folarin, O., Adeoti, L., Adegbola, R. B., & Adeogun, O. Y. (2020). Application of aeromagnetic data to map subsurface structural features in Ewekoro, Southwestern Nigeria. *Modeling Earth Systems and Environment*, *6*(4), 2291–2302. https://doi.org/10.1007/s40808-020-00812-y

Ishola, K. S., Fatoyinbo, A. A., Hamid-Mosaku, A. I., Okolie, C. J., Daramola, O. E., & Lawal, T. O. (2023). Groundwater potential mapping in hard rock terrain using remote sensing, geospatial and aeromagnetic data. *Geosystems and Geoenvironment*, *2*(1), 100107. https://doi.org/10.1016/j.geogeo.2022.100107

Keating, P., & Pilkington, M. (2004). Euler deconvolution of the analytic signal and its application to magnetic interpretation. *Geophysical Prospecting*, *52*(3), 165–182. https://doi.org/10.1111/j.1365-2478.2004.00408.x

Khan, A. N., Kim, B. W., Rizwan, A., Ahmad, R., Iqbal, N., Kim, K., & Kim, D. H. (2023). A New Method for Determination of Optimal Borehole Drilling Location Considering Drilling Cost Minimization and Sustainable Groundwater Management. *ACS Omega*, *8*(12), 10806–10821. https://doi.org/10.1021/acsomega.2c06854

Mabee, S. B., Curry, P. J., & Hardcastle, K. C. (2002). Correlation of Lineaments to Ground Water Inflows in a Bedrock Tunnel. *Groundwater*, *40*(1), 37–43. https://doi.org/10.1111/j.1745-6584.2002.tb02489.x

Mangs, A. D., Ejepu, J. S., Nkemkah, C. C., Yusuf, S. N., Sallau, A. K., Yakubu, J. A., Ibrahim, Y., & Wakili, W. M. (2023). Groundwater Potential Mapping in Lapan Gwari Community Using Integrated Remote Sensing and Electrical Resistivity Soundings. *International Journal of Geosciences*, *14*(08), 719–732. https://doi.org/10.4236/ijg.2023.148039

McCurry, P. (1975). The Geology of the Precambrian to Lower Palaeozoic Rocks of Northern Nigeria. In CA Kogbe (Ed.), *Geology of Nigeria*.

McCurry, P. (1976). The Geology of The Precambrian to Lower Paleozoic Rocks of Northern Nigeria. In *Geology of Nigeria* (CA Kogbe, pp. 15–38). : Elisabeth Publication Company.

Mohamed, A., Othman, A., Galal, W. F., & Abdelrady, A. (2023). Integrated Geophysical Approach of Groundwater Potential in Wadi Ranyah, Saudi Arabia, Using Gravity, Electrical Resistivity, and Remote-Sensing Techniques. *Remote Sensing*, *15*(7), 1808. https://doi.org/10.3390/rs15071808

Mohamed, W. H., Elyaseer, M. H., & Sabra, M. E. M. (2023). Structural lineament analysis of the Bir El-Qash area, Central Eastern Desert, Egypt, using integrated remote sensing and aeromagnetic data. *Scientific Reports*, *13*(1), 21569. https://doi.org/10.1038/s41598-023-48660-x

Mpofu, M., Madi, K., & Gwavava, O. (2020). Remote sensing, geological, and geophysical investigation in the area of Ndlambe Municipality, Eastern Cape Province, South Africa: Implications for groundwater potential. *Groundwater for Sustainable Development*, *11*, 100431. https://doi.org/10.1016/j.gsd.2020.100431

Nyaberi, D., Barongo, J., Kariuki, P., Ogendi, G., & Basweti, E. (2019). Groundwater Resource Mapping through the Integration of Geology, Remote Sensing, Geographical Information Systems and Borehole Data in Arid-Subarid Lands at Turkana South Sub-County, Kenya. *Journal of Geoscience and Environment Protection*, *07*(12), 53–72. https://doi.org/10.4236/gep.2019.712004

Offodile, M. E. (1992). *Ground Water Resources of Nigeria*. Medico Limited.

Ogezi, A. E. (1998). *Geochemistry and Geochronology of Basement Rocks from North Western Nigeria*. University of Leeds. .

Olorunfemi, M. O., & Oni, A. G. (2019). Integrated geophysical methods and techniques for siting productive boreholes in basement complex terrain of southwestern Nigeria. *Ife Journal of Science*, *21*(1), 13. https://doi.org/10.4314/ijs.v21i1.2

Ouattara, S. G., Dibi, B., & Mangoua, J. M. O. (2021). Contribution of RADARSAT-1 Images to Structural Geological Mapping and Lineament Density Assessment in the Lobo River Watershed at Nibéhibé (Centre-West, Côte d'Ivoire). *European Journal of Environment and Earth Sciences*, *2*(4), 15–20. https://doi.org/10.24018/ejgeo.2021.2.4.147

Park, Y.-J., Lee, K.-K., & Kim, J.-M. (2000). Effects of highly permeable geological discontinuities upon groundwater productivity and well yield. *Mathematical Geology*, *32*(5), 605–618. https://doi.org/10.1023/A:1007514405501

Prabu, P., & Rajagopal, B. (2013). Mapping of Lineaments for Groundwater Targeting and Sustainable Water Resource Management in Hard Rock Hydrogeological Environment Using RS- GIS. In *Climate Change and Regional/Local Responses*. InTech. https://doi.org/10.5772/55702

Sadiq, F.K., Maniyunda, L.M., Adegoke, K.A., and Anumah, A.O. (2021). Evaluating quality of soils formed on basement complex rocks in Kaduna State, northern Guinea savanna of Nigeria. *Environmental Monitoring and Assessment*, 193: 383 – 398. https://doi.org/10.1007/s10661-021-09157-0

Sarwar, A., Ahmad, S. R., Rehmani, M. I. A., Asif Javid, M., Gulzar, S., Shehzad, M. A., Shabbir Dar, J., Baazeem, A., Iqbal, M. A., Rahman, M. H. U., Skalicky, M., Brestic, M., & EL Sabagh, A. (2021). Mapping Groundwater Potential for Irrigation, by Geographical Information System and Remote Sensing Techniques: A Case Study of District Lower Dir, Pakistan. *Atmosphere*, *12*(6), 669. https://doi.org/10.3390/atmos12060669

Takorabt, M., Toubal, A. C., Haddoum, H., & Zerrouk, S. (2018). Determining the role of lineaments in underground hydrodynamics using Landsat 7 ETM+ data, case of the Chott El Gharbi Basin (western Algeria). *Arabian Journal of Geosciences*, *11*(4), 76. https://doi.org/10.1007/s12517-018-3412-y

Tam, V. T., De Smedt, F., Batelaan, O., & Dassargues, A. (2004). Study on the relationship between lineaments and borehole specific capacity in a fractured and karstified limestone area in Vietnam. *Hydrogeology Journal*, *12*(6), 662–673. https://doi.org/10.1007/s10040-004-0329-1

Tawey, M. D., Udensi, E. E., Adetona, A. A., & Alhassan, U. D. (2019). Identification of Lineaments within Gitata Using Derivative, Euler Deconvolution and Centre for Exploration Targeting CET. In *International Journal Of Science For Global Sustainability* (Vol. 5, Issue 1).

Velis, M., Conti, K. I., & Biermann, F. (2017). Groundwater and human development: synergies and trade-offs within the context of the sustainable development goals. *Sustainability Science*, *12*(6), 1007–1017. https://doi.org/10.1007/s11625-017-0490-9

Wiederhold, H., Kallesøe, A. J., Kirsch, R., Mecking, R., Pechnig, R., & Skowronek, F. (2021). Geophysical methods help to assess potential groundwater extraction sites. *Grundwasser*, *26*(4), 367–378. https://doi.org/10.1007/s00767-021-00495-x