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Analysis of high-resolution aeromagnetic data of geological transition zones of the southeastern part of Bauchi, NE Nigeria

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ABSTRACT

The study investigated the subsurface tectonic framework and structural disposition of the basement/sedimentary transition zone in the southeastern part of Bauchi, Northeastern Nigeria, to delineate the basal and lateral contacts and unravel some of the hydrogeological and engineering challenges in such areas. The method deployed involved the analysis of high-resolution aeromagnetic data, through the application of several filtering techniques. The transformation techniques applied include reduction to pole, second vertical derivative techniques using analytical signal, and Euler deconvolution. The Euler depth result range of 1–200 m coincides with the region where basement rocks outcrop on the surface, while the depth range between 0 and –800 m corresponds to the sedimentary terrain (the Kerri-Kerri formation) or part of the area where the basement rocks are overlain by thick overburden sediments. The 2-D depth model around the transition zone showed high variability as it ranged from 0 to –500 m owing to the presence of basement highs and depressions. The basement highs are usually characterized by impermeable rocks with poor aquifer characteristics and are responsible for the failure of boreholes in these zones. The basement depressions, however, constitute good groundwater prospects depending on the hydrological properties of the sedimentary infill. The general orientation of lineaments in the area revealed NW–SE, NE–SW, and ENE–WSW, with minor N–S and E–W trends, suggesting a pan-African origin. The occurrence of lineaments in parts of the contact zones also contributes to the groundwater prospects. The erratic bedrock relief exhibited by the study area is also detrimental to the foundation of pavement structures as it undermines their durability. Therefore, a detailed site investigation is crucial in such geological contact zones prior to the erection of structures. Additionally, vertical electrical soundings are recommended before borehole drilling to ascertain the suitability of these hydrogeological complex zones.

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1. Introduction

Geological transition zones can be described as contact zones between older crystalline rocks and younger sedimentary formations. These zones are known for

their poorly defined lateral and basal contacts which in most cases constitute serious challenges for engineering and hydrogeological endeavors (Osinowo and Olayinka, 2013). Consequently, numerous misleading judgments of geological consequence have been

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made in such zones owing to the difficulty associated with the lithological characterization of the area as either a crystalline basement or sedimentary terrain. While purely basement or sedimentary settings are relatively unambiguous, geological transition zones, which are intricate combinations of these different rock settings, have proved to be indiscernible and problematic, especially in the area of groundwater occurrence/development and foundation of engineering structures. Groundwater exploitation has faced some challenges (pitfalls) in such zones because the occurrence and distribution of groundwater resources within transition zones are immensely influenced by the configuration of the underlying basement which ultimately determines the thickness of the overburden units. The hydrogeological value of basement topography has been well documented by [Dan-Hassan and Olorunfemi \(1999\)](#), [Bala and Ike \(2001\)](#), and [Osinowo and Olayinka \(2013\)](#). These studies suggest that most prolific zones for groundwater exploitation are discernible from the basement topography map, as basement troughs are usually associated with thick saprolitic units as compared to basement ridges which correspond to poorly weathered and resistive regoliths of low groundwater potential. A high incidence of abortive boreholes has been reported in geological transition zones attributable to the occurrences of envisaged shallow basement rocks in a seemingly sedimentary terrain. Furthermore, engineering projects, e.g., road construction in such problematic zones, have faced similar problems because the shallow bedrock significantly influences the mechanical behavior of pavements. Therefore, there is the need to unravel the intricacies in such geologically complex zones using available scientific techniques to forestall some of the hydro-engineering challenges associated with these terrains.

Different techniques ranging from conventional geological mapping to Geographic Information System (GIS) and geophysical approaches have been applied by researchers to characterize geological contact zones ([Ariyo and Adeyemi, 2016](#); [Lawal et al., 2020, 2021](#); [Osinowo and Olayinka, 2013](#)). Geological maps represent traditional methods of acquiring spatial data and delineating different rock units ([Jones et al., 2009](#)). These maps are commonly derived from geological field mapping, logging of stream exposures, and interpretation of borehole lithological logs ([Adegoke et al., 1978](#); [Dike, 1993](#)), as well as from regional studies and remotely sensed data ([Ferre and Caby, 2007](#)). Unfortunately, these methods have their limitations. For instance, the accuracy of geological

maps is affected by the paucity of outcrop stream channel exposures and borehole data, which ultimately affects the inferred geological boundaries between rock units ([Feyisa et al., 2014](#); [Jones et al., 2009](#); [Minor et al., 1994](#)). In a similar vein, the subjective nature of interpretation of remotely sensed data cannot be overlooked. Geophysical techniques, notably magnetic ([Osinowo and Olayinka, 2013](#)) and resistivity methods ([Ariyo and Adeyemi, 2016](#); [Lawal et al., 2020](#)), serve to complement the classical mapping techniques as they can utilize certain physical properties of the rocks (i.e., magnetic susceptibility, conductivity, or resistivity) to provide spatial information and analysis of overburden units and basement topography of an area of interest ([Nasuti et al., 2012](#)). The strength of the aeromagnetic method lies in the fact that it measures the magnetic susceptibility of rocks and given that sedimentary rocks are usually devoid of magnetic minerals, whereas basic and ultrabasic rocks have higher magnetic susceptibility making them vital in distinguishing sedimentary and overburden soils from the underlying bedrock ([Mekonnen, 2004](#)). The electrical resistivity method is also a good technique for geological transition zones; however, the technique is limited by its high cost and the fact that its accuracy diminishes with distance away from the survey point, especially in the basement terrain ([El Bastawesy et al., 2019](#)).

It is important to mention that most of the available literature on geological transition zones, resistivity, and magnetic techniques have been deployed to study the southwestern contact zones between the Precambrian basement complex of Nigeria and the Cretaceous sediments ([Ariyo and Adeyemi, 2016](#); [Osinowo and Olayinka, 2013](#)), and the few works that have been carried out in the northeastern geological transition (study area), which falls between basement complex rocks and tertiary (Paleocene) sedimentary units, have not focused on the transition zones. For instance, [Lawal et al. \(2020\)](#) applied GIS to resistivity data for the characterization of aquifers in the Bauchi-Alkaleri-Kirfi transition zone (study area), while [Lawal et al. \(2021\)](#) deployed secondary geoelectrical parameters to characterize the protective capacity of the aquifer system in the study area. Other classical studies in the region include [Dike \(1993\)](#) and [Dike and Egbuniwe \(1993\)](#), who carried out the detailed lithostratigraphic correlation of the facies of the Kerri-Kerri formation using borehole data and outcrops, and also studied the unconformity around Maina Maji area of the study region. Furthermore, [Abubakar et al. \(2010\)](#) studied the evolution of the Gongola arm of the Upper

Benue Basin using spectral analysis of aeromagnetic data. These studies have not provided adequate information on the basement configuration and the lateral and basal contact of the rocks in the study area and such data are very consequential in the aspects of groundwater development and foundation studies in these complex zones.

The main objectives of this study are, therefore, to determine the depth to the basement surface, examine the lateral and basal contacts of the rocks, identify the basement structures, and evaluate the groundwater potential in these hydrogeological complex zones using high-resolution aeromagnetic (HRAM) data of the area.

2. Study Area

The study area lies within longitudes 10°00' and 10°30'E and latitudes 10°00' and 10°30'N. The region

is underlain by the Precambrian-age basement complex to the west (Fig. 1), with geomorphic units ranging between 275 and 706 m above sea level. The Kerri-Kerri subbasin (275–537 m above sea level.) lies easterly and is underlain by Paleocene-age sediments of the Northern Benue Basin.

The region is drained by the Dindima River which has a characteristic dendritic pattern and runs from the southwestern to the northeastern part. The Mansuri River drains the eastern part, and the southwestern zone is drained by the Yashi River. The average yearly rainfall varies between 840 and 1,085 mm (Buba et al., 2015). The average annual temperature in the study area varies between 25°C and >33°C in December and February, respectively, but could be considerably higher (40°C) in the extreme dry season (Buba et al., 2015).

In terms of geology, the area lies within the transition zones of the Precambrian basement complex rocks

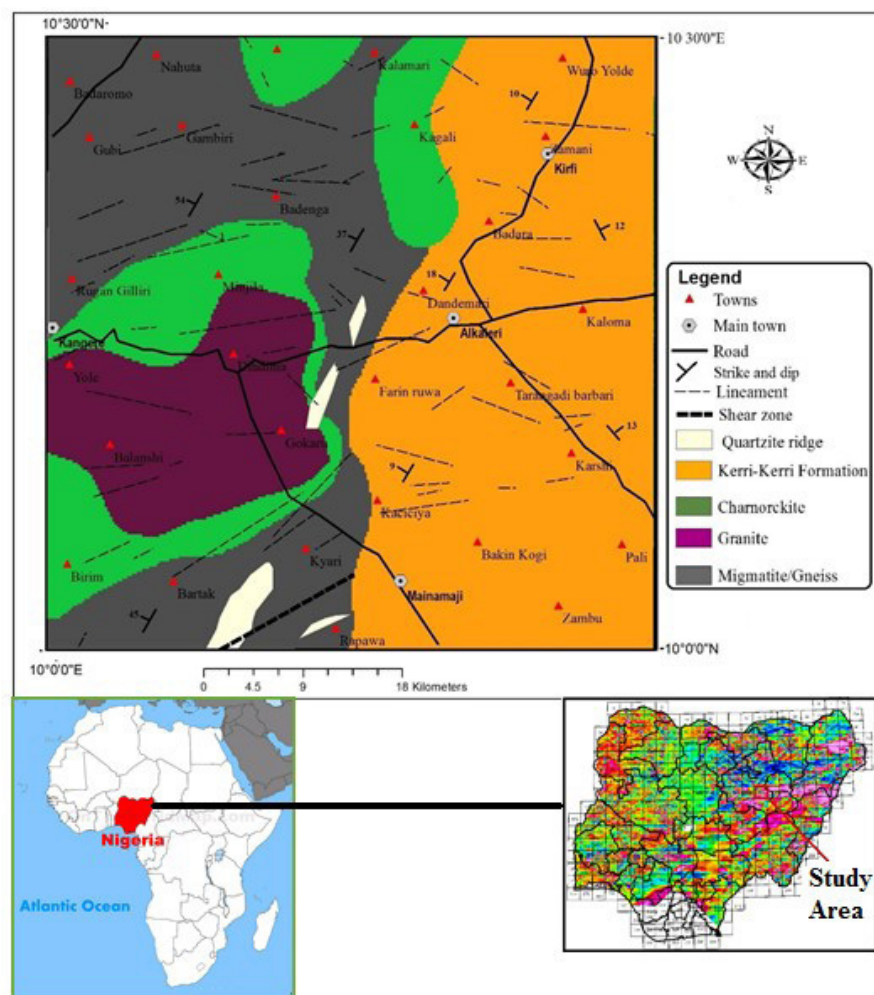


Figure 1. Geological map of the study area with an inset map of Africa and Nigeria showing the location of the study area.

and the Paleocene Kerri-Kerri formation, a part of the Northern Benue Basin of Nigeria (Fig. 1). The basement complex rocks are primarily migmatite and gneiss, which were intruded by charnockites, biotite granites, and biotite hornblende granites during the Neoproterozoic episode (Ferre and Caby, 2007). The sedimentary rocks in the area are believed to have been deposited in various environments which include fluvial, deltaic lacustrine (Adegoke et al., 1978; Dike, 1993) and consist of coarse-medium sandstones, grits, pebbly sands interbeddings of gravely sands, fine-medium sandstones, siltstones, and clays. The commonest lithology in the formation is the medium-coarse sandstones which also constitute the main aquifer units (Dike, 1990). The Kerri-Kerri formation has been dated Paleocene from palynological studies (Adegoke et al., 1978).

The hydrogeology of the area can be divided along geological lines, with the basement aquifers consisting of saprolitic units (weathered regoliths) and sap rocks (fractured bedrocks). The average yield of wells in the weathered regolith aquifers of the basement settings ranges from 0.1 to 1 l/second. However, better yields have been recorded where these weathered units are underlain by fractured bedrocks (Tijani et al., 2016). In the sedimentary terrain, however, the aquifers are mostly the pore-type, i.e., porous and permeable sandstones. The Kerri-Kerri falls within the consolidated sedimentary rocks hydrogeological setting, which is usually characterized by high borehole yields (10–50 l/second) (Tijani et al., 2016). Depending on the elevation of the region, these aquifers are gravely or clayey at depths of 20–155 m (Dike, 1993).

3. Materials and Methods

3.1. Aeromagnetic data acquisition

The preprocessed aeromagnetic data for the study area was acquired from the Nigerian Geological Survey Agency (NGSA) as residual magnetic intensity. The data was collected by Fugro Airborne Surveys for the NGSA between 2001 and 2009. Magnetic data recording was carried out at intervals of 0.1 seconds or less than 7 m. Sensor mean terrain clearance was 80 m, with a flight line spacing of 500 m and tie-line spacing of 5,000 m. The flight line trend was 1,350 and the tie-line trend was 450. Scintrex CS3 Cesium Vapor magnetometer was used and the data acquisition system was FASDAS. King KR405 and King KR405B were the types of radar altimeter used, while the barometric altimeters used were ENVIRO BARO and DIGIQUARTZ. Flight-path tracking was digital using Novatel 3151R and Omnistar RTDGPS for flight-path navigation.

3.2. Data processing and enhancement

Data corrections which include elimination of temporal variations, height corrections, and removal of the International Geomagnetic Reference Field (IGRF) were also carried out by Fugro Airborne Services on behalf of the agency as part of preprocessing. Arising from the preprocessing of the aeromagnetic data, data enhancement and detailed analysis of the resulting residual magnetic intensity data followed. The enhancement techniques employed include reduction to the equator (RTE), upward continuation approach, and horizontal component of tilt derivative (TDR) were obtained and used as a starting grid for lineaments extraction because of its independence to inclination and declination. In addition, analytical signal and Euler deconvolution were also derived from the residual magnetic intensity data. Given that the research area has relatively low latitudes, the RTE was adopted to correct for inclination and declination of the Earth's magnetic field. The RTE is best suited for low latitude regions or areas in the vicinity of the equator, while the reduction to pole is more effective in other cases (Luo et al., 2010). The overall goal of the RTE is to center the zeniths of magnetic anomalies with those of the causative bodies to improve data interpretation.

Following the RTE corrections, an upward continuation filter was applied. This filter is particularly very efficient in smoothening the data by removing noise and the effects of very shallow sources while enhancing deeper signals, which are presumed to be of geologic origin (Osinowo and Olayinka, 2013). The procedure is achieved by attenuating short-wavelength anomalies relative to regional long-wavelength anomalies, thereby enhancing deep-seated structures (Blakely and Simpson, 1986). The aeromagnetic data were upwardly continued to a distance of 500 m, considering that the study was dealing with a contact zone where relatively shallow signatures are expected. The TDR and its derivatives (THDR_TDR) TDR and THDR_TDR are very effective in exploring mineral targets and mapping shallow basement structures (Miller and Singh, 1994). In the present study, TDR was deployed in mapping structural lineaments. Specifically, the TDRs grid was deployed as the initial grid for the Centre for Exploration Targeting (CET) grid analyses in line with Verduzco et al. (2004).

The analytical signal is given as the square root of the sum of vertical derivatives of total magnetic field intensity in the x -, y -, and z -directions. As shown in Equation 1, the analytic signal is the square roots of the sums of the squares of the first order of two horizontal

derivatives (x and y) and a vertical component (z) (Macleod et al., 1993). This analysis was carried out to map and delineate the boundaries of different geologic features as follows (Eq. 1):

$$\text{Analytical Ssignal}(xyz) = \left(\left(\frac{\delta T}{x} \right)^2 + \left(\frac{\delta T}{y} \right)^2 + \left(\frac{\delta Z}{z} \right)^2 \right)^{0.5} \quad (1)$$

Euler deconvolution, an inverse method of depth-to-source estimation, was adopted for this study. In doing so, the potential field depth originating from a basement rock or other magnetic anomalous source is estimated as outlined by Nabighian and Hansen (2001). The procedure is based on Hilbert transform equations and put forward by Mushayandebvu et al. (2001). Euler deconvolution computes the source location of an anomaly using the magnetic field (T) and its gradients (Pilkington and Keating, 2017). This method is effective in locating causative sources, intrusions, and contacts with reliable precision.

4. Results and Discussion

4.1. Residual magnetic intensity

The residual magnetic intensity map of the study area is shown in Figure 2. A general outlook of this map reflects the shapes of the anomalies prior to transformation to the top of their causative bodies. The map shows some major magnetic bands distributed around

the various parts of the map. Very high positive anomalies with amplitudes of about 181–214 nT and a NE–SW trend are visible in the southern parts of the study area. High positive anomalies with amplitude of 112–181 nT are, however, notable in the northeastern, central, and southeastern parts of the study area. The moderate to low positive anomalies (17–112 nT) can be observed in the northern zones of the study area, with pockets in the southern parts. The negative anomalies are with an amplitude of about –0.3 to –50 nT, which covers the northern and southeastern parts of the study region. These anomalies (negative) reveal a characteristic NW–SE trend. However, other NE–SW trending negative anomalies are discernible in the northwestern and southwestern parts of the area.

A closer look at the immediate zones of geological transition or contact area (Fig. 2) demonstrates that the distribution of the residual magnetic intensity is somewhat variable, comprising very high to high positive anomalies (112–214 nT) to the south and central parts of the transition zones, while the northern parts revealed moderate-to-low positive anomalies (17–112 nT) as well as negative anomalies (–0.3 to –50 nT).

4.2. Analytical signal map

The analytic signal amplitude over the study area (Fig. 3) ranges from 0.0007 to 0.088 nT/m and averages 0.036 nT/m. The analytical signal is divided into

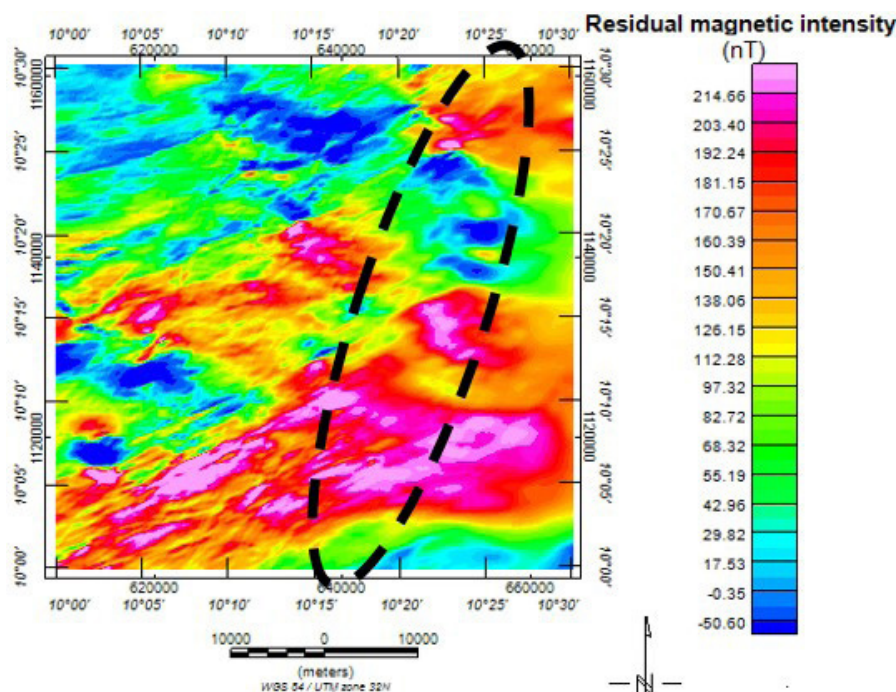


Figure 2. Residual magnetic intensity of the study area (reduced to equator) showing the geological transition zones (dotted oblong-shaped dark lines).

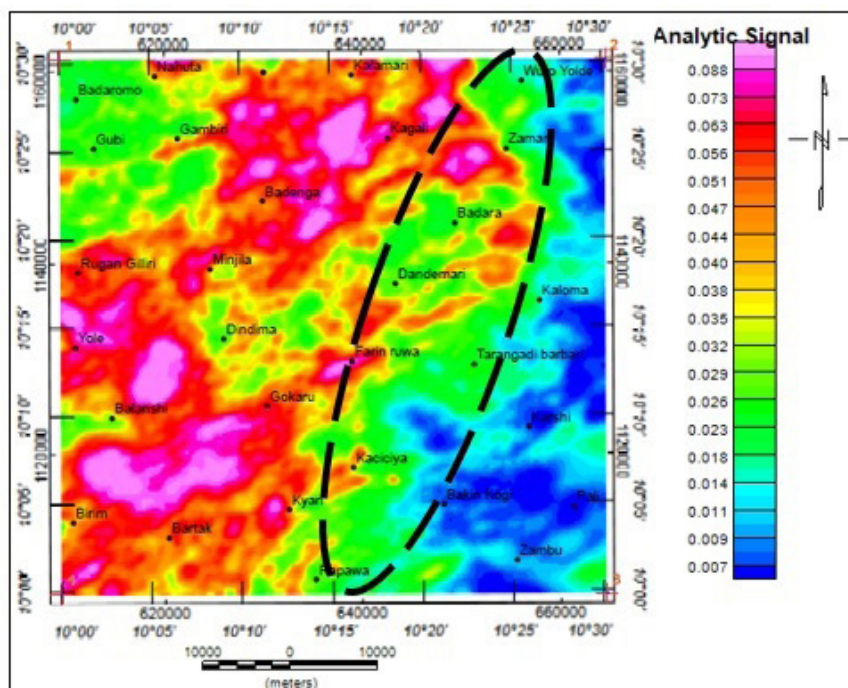


Figure 3. Analytical signal map of the study area (the thick dotted line showing the transition zones).

different color bands with each having different magnetic signatures. The bands range from blue (0.007–0.018 nT/m) through green (0.018–0.032 nT/m), yellow (0.032–0.038 nT/m), brown (0.038–0.051 nT/m), red (0.051–0.063 nT/m) to purple (0.063–0.088 nT/m) in ascending order. Prominent amplitude anomalies (red–purple bands) predominate the basement complex zones of the area as observable around Rukan Gilliri, Minjila, Badanga, Nahuta, and Kagali in the northwestern and northern parts of the map. High signals also characterized Yole, Kyari, Gokaru, and Balanshi in the southwestern part of the analytical signal map. High amplitude analytic signal anomaly reflects high magnetic intensity contrast between crystalline basement rocks (positive magnetic intensity). Conversely, the areas with relatively thick sedimentary piles correspond to low magnetic intensity (blue bands) within the sedimentary units of the Paleocene Kerri-Kerri basin.

The green-colored bands occupy most of the geological transitional zones and parts of the basement complex with considerably thick overburden as exemplified in Badaromo and Gubi areas in the extreme northwestern and central parts of the study area (around the Dindima River). The yellow and the brown bands represent basement zones with relatively thin overburden sediments. Generally speaking, the basement complex zones display higher analytical signals as compared

to the sedimentary zones. However, some parts of the basement revealed a comparatively thick sedimentary pile (overburden) in the basement terrain which could be of hydrogeological advantage. The geological contact zones demarcated in Figure 3 show some variability in the analytical signal amplitude as a protrusion of high signals can be observed in the northeastern zone of the transition zone (between Zamani and Badara areas). Zones of shallow basement are also notable in the central (around Dandamari) and northeastern parts of the transition zone, which are supposedly part of the Kerri-Kerri formation based on the NGSA (2006) and Lawal et al. (2020). The southern half of the transition zone revealed considerably thicker overburden units, especially in the Tarangadi area; however, some areas with shallow basements are also discernible (Farin Ruwa, Kacchiya, and Rapawa). These areas represent an extension of the Precambrian basement complex zones which are the primary rocks in the region. It can thus be concluded from the above premise that the original lateral boundaries inferred by previous literature (Dike, 1993; Lawal et al., 2020; NGSA, 2006) need to be reviewed as revealed by the analytical signal map (Fig. 3).

4.3. Euler deconvolution (depth to basement estimation)

The qualitative interpretation of the residual magnetic data (Fig. 4) using the Euler deconvolution technique

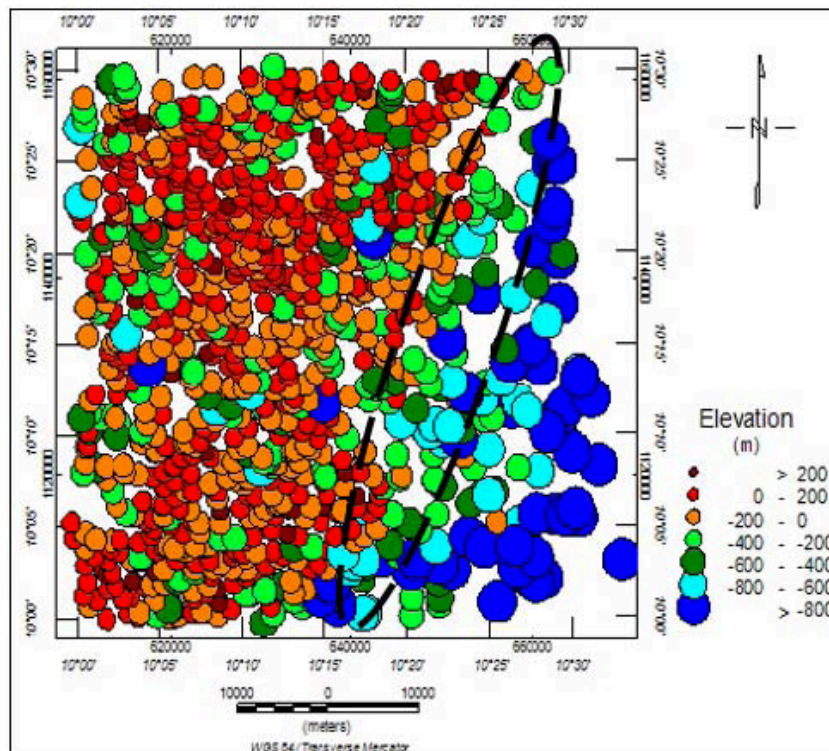


Figure 4. Euler deconvolution classified plot of the area.

indicated that the depth to the basement surface in the investigated area ranges from 0 to >800 m (Fig. 4). The Euler deconvolution solution points correspond to regions of high analytic signal amplitude and by implication would represent regions with meaningful anomalies whose Euler depth shall provide information of geomorphological and geological significance. The Euler depth solutions are presented as color-coded circles, with the circle's colors indicating depth range and the circle size reflecting depth variation within the range. It is evident from the circle sizes that the depths in the basement complex areas are highly variable as compared to those of the sedimentary areas.

Euler depth solutions were referenced to Minna datum in Nigeria and all negative solutions correspond to magnetic sources below the mean sea level, while positive solutions represent depth values above mean sea level. Euler depth results range of 1–200 m coincides with regions where basement rocks outcrop on the surface, while the depth range between 0 and –800 m correspond to the sedimentary terrain (Kerri-Kerri formation) or part of the area where the basement rocks are overlain by thick overburden sediments. However, some pockets of comparatively deep areas were recorded in the extreme northwestern portions, some isolated parts of the basement complex, and they are believed to coincide with deeply faulted and

downthrown zones as most of the so-called areas tend to have high lineament densities. Solutions around the basement complex areas indicate basement source, which is greater than 45 m in depth and progressively gets deeper in the northern and southwestern parts (Fig. 4). The deeper most of the area (1,045 m) lies in the southeastern zones, underlain by the Kerri-Kerri formation as revealed by the 2-dimensional depth to basement map and 3D model derived from the Euler deconvolution data (Figs. 5 and 6).

According to Dike (1993), the sediment fills thickness in the Kerri-Kerri basin is estimated at over 320 m for the west (where the study area lies) and the central and becomes thinner eastward to about 262 m. The present study revealed a maximum sediment thickness of over 1,045 m (Figs. 5 and 6) for the western margin of the Kerri-Kerri basin, which is far higher as earlier workers made estimates based on boreholes and stratigraphic data. The present work, however, employed a HRAM data. The general outlook of the Euler depth maps is in tandem with the analytical signal maps as the maps can be divided into three different parts based on the sizes of the Euler depth solutions (colors). The basement setting (western parts) is dominated by the smaller red- to brown-colored circles which indicate outcropping units (0–200 m) and depths of about 0–45 m (Figs. 4 and 5). Conversely, the

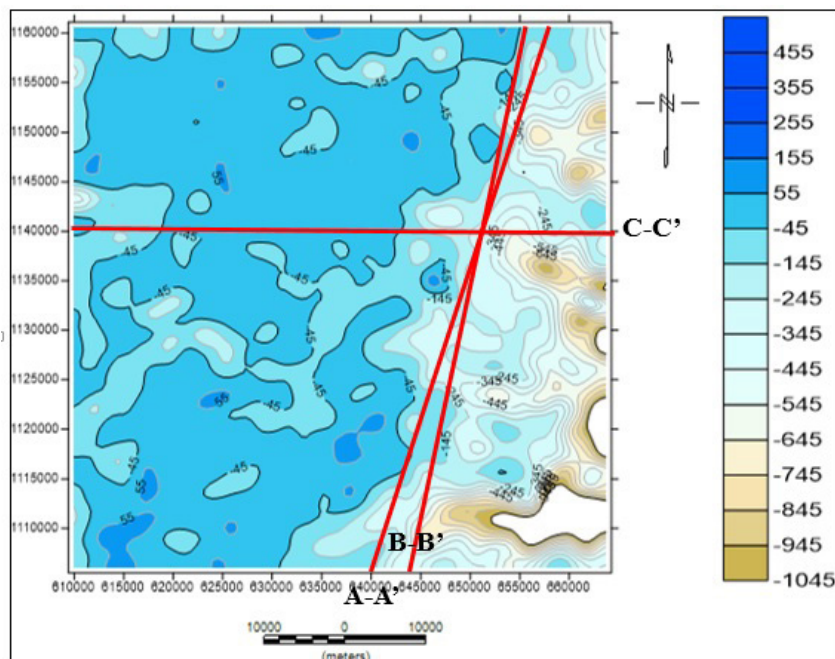


Figure 5. 2-D basement topography map of the study area.

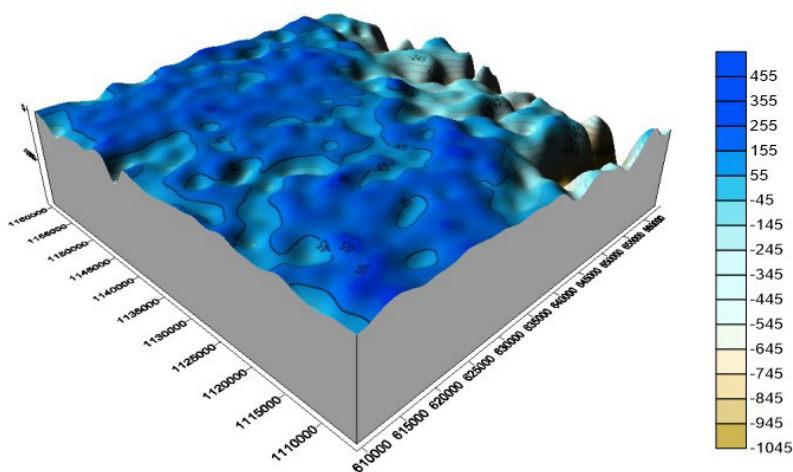


Figure 6. 3-D basement configuration model of the study area derived from the Euler deconvolution data.

sedimentary zones which underlie the eastern zones can be seen to be dominated by the larger circles (light and dark blue colored), suggestive of deeper magnetic sources and thus thicker sedimentary fills.

Between the basement and sedimentary zones lies an intermediate zone (transition), where you have the smaller red- and brown-colored circles embedded within the intermediated and the larger circles. This scenario reflects an erratic basal contact between the basement and sedimentary interface, which is considered a problematic zone for groundwater development (Osinowo and Olayinka, 2013). To further unravel the

nature of this basal contact, three cross-sectional profiles A-A', B-B', and C-C' were purposively drawn from the Euler depth to basement contour map of the study area (Fig. 7a-c).

Cross-sections A-A' and B-B' (Fig. 7a and b) both run from southeast to northeast and reveal the nature of the basement configuration and the thickness of the sedimentary deposits in the immediate zones of geological transition. As can be observed from these sections, the topography of the basement in the contact zones is somewhat nonuniform and erratic as compared to the cross-section C-C (which runs from the basement

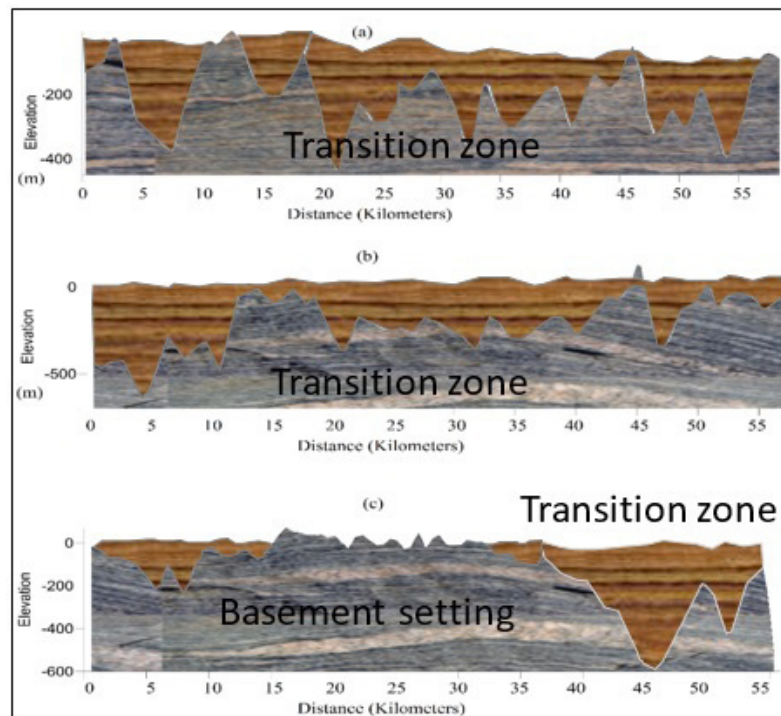


Figure 7. Cross-sectional profiles of basement topography across the study area. (a) A-A', (b) B-B', and (c) C-C'.

setting to the sedimentary terrain) which shows some level of uniformity, especially in the basement sections.

Profile A-A' passes through Rapawa, Kaciciya, Tarangadi, Dandimari, Badara, and Wuro Yolde in the northeastern part of the area. In this profile, elevations of the underlying Precambrian basement complex vary between 0 m around Wuro Yolde to about -400 m in Rapawa area in the south suggesting an undulating basement topography along the transitional boundaries. The profile revealed that the zones are characterized by several magnetic highs which could constitute hydrogeological problematic areas and sometimes influence civil engineering design and construction (Osinowo and Olayinka, 2013). Profile B-B', which is just about 2 km to profile A-A', revealed a similar basement configuration; however, the basement elevation in the latter exceeds -500 m. A different trend of basement relief can be observed from profile C-C', where the basement complex setting showed an even and less rugged topography as revealed by western parts of the area. However, in Dandemari, which lies to the eastern parts of the study area around the geological transition zone, the incidence of rugged and undulating bedrock relief is evident. Although this study's main focus is the geological transition zones, it is noteworthy that the western parts of the basement terrain (Rugan Gilliri) showed thicker overburden layers

(45–200 m), hence better groundwater prospects as compared to the central parts (Minjila), which are mostly outcropping.

The general outlook of the geological transition revealed by the Euler depth maps is in tandem with the analytical signal maps in that there are variations in these zones. The analysis of the Euler profiles indicated that rugged and undulating basement topography typifies the areas around the contact zone, while the basement settings revealed nearly even basement relief.

4.4. Magnetic lineaments

The distribution of the lineaments in the bedrocks that underlie the transition zones of the study area is shown in Figure 8, and the rose diagram showing the structural trends is shown in Figure 9. The lineament patterns are NW–SE, NE–SW, and ENE–WSW, with a few E–W and N–S directions. The major trends observed correspond to those of the pan-African event (Ajakaiye et al., 1986), while the minor ones have been linked to the tectonism of Jurassic and end-Cretaceous periods (Dike, 1993). Linear structures are excellent pointers of major structural trends as their orientation usually conforms to regional geology (Dobrin and Savit, 1988). The lineaments can be regarded as representational of the structural expression of a given area because of

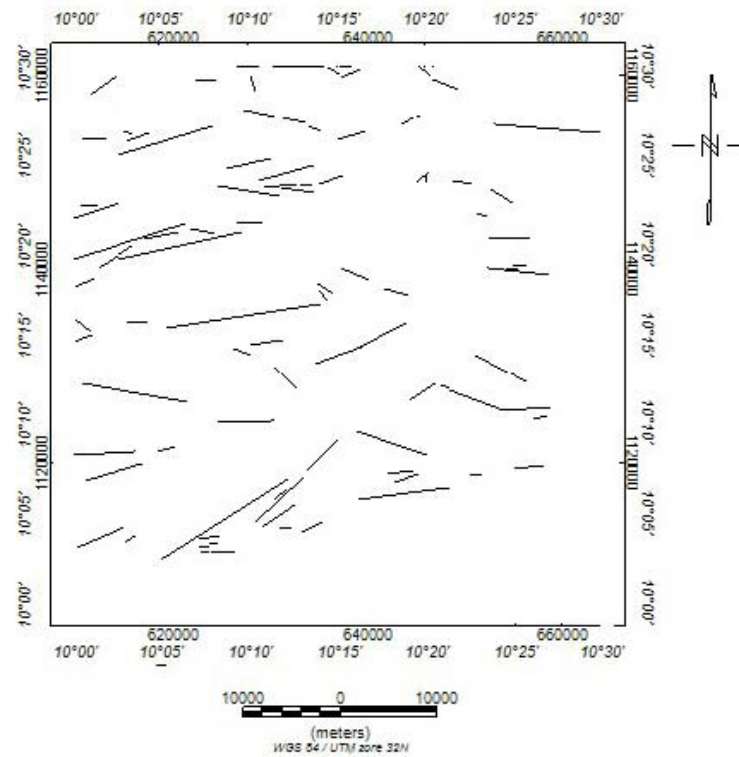


Figure 8. Magnetic lineament map of the study area.

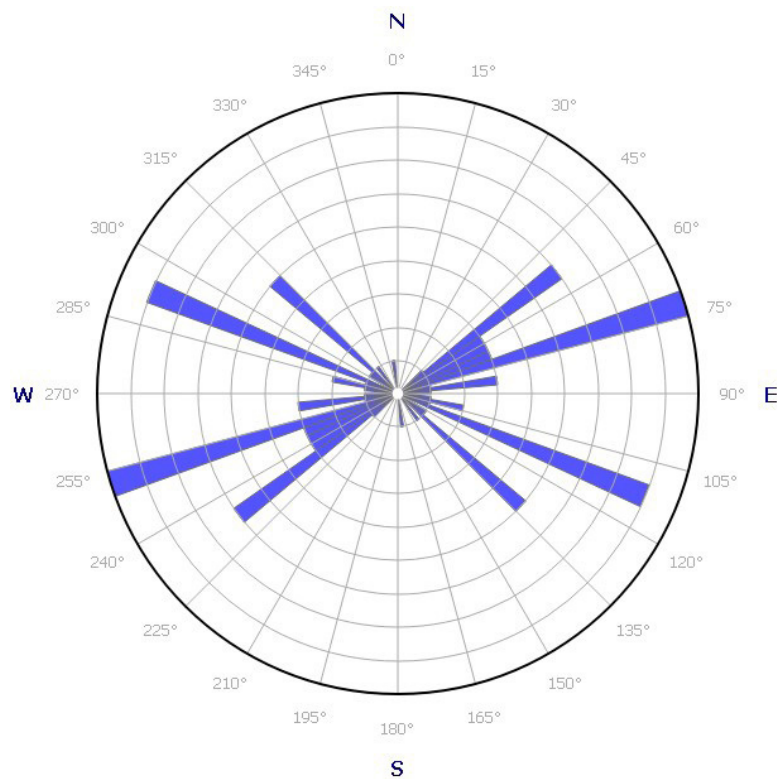


Figure 9. Rose diagram showing lineament trends.

their good connection with structures mapped in the field (Morelli and Piana, 2006). Groundwater exploration in basement settings has traditionally relied on lineament analysis as lineaments reflect increased permeability in hard rocks and areas of high fracture density or fracture intersection are likely to have high groundwater potential (Edet et al., 1998; Lawal et al., 2020; Magowe and Carr, 1999). Consequently, water wells sited on or at the vicinity of lineaments are generally more productive than those drilled in areas without lineament (Adiat et al., 2012).

4.5. Hydrogeological and geotechnical implications

Understanding the relief and structure of basements at geological transition zones has shown to be quite useful in determining groundwater potential and making certain decisions in civil engineering endeavors. Olorunfemi et al. (1999), Bala and Ike (2001), Ariyo and Adeyemi (2016), and Osinowo and Olayinka (2013), amongst others, have recognized the hydrogeological relevance of the bedrock relief. Basement depression usually represents areas of groundwater accumulations, except when these troughs are filled with aquicludes as is the case in geological contact zones of Chad formation (Mohammed, 2016). However, basement highs are naturally impervious zones with no potential for groundwater. The erratic combination of basement highs and troughs covered with sedimentary deposits in the geological transitional zones of Bauchi and others makes them hydrogeologically complex and problematic. The southeastern and the central parts of the geological contact zones exemplified by Rapawa, Bakin Kogi, Farin ruwa, and Dandemari indicate some basement troughs which could constitute potential sites for groundwater collection (Mohammed, 2016). Furthermore, some basement highs are discernible in the southeastern (Kaciciya) and northeastern parts (Wuro Yolde, Zamani, and Badara) of the area which is suggestive of zones of low permeability and low groundwater prospects.

Additionally, when different tectonic episodes have resulted in a high degree of faulting and folding, joints, and fracture systems in the buried bedrocks, this could have a remarkable effect on the overall groundwater potential of the area as these structures might constitute openings for the storage of groundwater (Mogaji et al., 2011). The occurrence of lineaments is notable along the transition zones of the study area. Dandemari, Tarangadi, and Kaciciya all displayed manifestation of lineaments, and in line with Adiat et al.'s (2012) study, boreholes drilled on lineaments are usually more productive as compared with

randomly sited wells. It is important to note, however, that lineaments founded on elevated and outcropping rocks may not reflect groundwater bearing conduits, but lineaments located in depressions exemplified by stream channels (structurally controlled streams) are generally the most prolific (Edet et al., 1998).

Furthermore, in the aspects of civil engineering construction, geotechnical investigations are recommended for all structures to be sited in areas with shallow bedrock. The investigation's goal is to find subsurface conditions that could be harmful to the environment or constitute a construction hazard to a proposed engineering structure. Shallow basement rocks under road alignment can significantly influence the mechanical responses of the pavement and must therefore be taken into account in the design. In the backcalculation of layer moduli for rehabilitation design, shallow bedrock is also a significant consideration (FHWA, 2006). According to Ademila (2021), irregular bedrock relief with associated basement highs, depressions, lineaments, and intense weathering of the bedrock in the foundation of pavement structures constitute a serious threat to the durability and service life of the highway. In light of the above, the study area would require thorough geotechnical evaluation to ascertain the subsurface bedrock configuration and characteristics of the area to mitigate any construction problems. Also, parts of the study area characterized by shallow bedrocks and lineaments (Zamani, Badara, Dandemari, Tarangadi, and Kaciciya) would require meticulous site investigation to ascertain the depths to bedrock, prior to emplacement of any engineering structure.

5. Summary and Conclusion

The analysis of HRAM data of the basement/sedimentary contact zones of the southeastern part of Bauchi has revealed valuable information on the subsurface architecture of these geologically intricate zones. The study indicated that rugged and undulating basement topography typifies the areas around the contact zone, while the basement settings revealed nearly even basement relief. The Euler depth result range of 1–200 m coincides with regions where basement rocks outcrop on the surface, while the depth range between 0 and –800 m corresponds to sedimentary terrain (Kerri-Kerri formation) or part of the area where the basement rocks are overlain by thick overburden sediments.

However, some pockets of comparatively deep areas were recorded in the extreme northwestern portions,

some isolated parts of the basement complex, and they are believed to coincide with deeply faulted and downthrown zones as most of the so-called areas tend to have high lineament densities. The 2-D depth model indicated a depth range of between 0 and –500 m around the geological transition zones and this variation is associated with some attendant hydro-engineering challenges. The study also revealed the major structural trends of lineaments in the bedrocks as NW–SE, NE–SW, and ENE–WSW trends.

The studied contact zone is characterized by basement troughs and basement highs, with the former constituting suitable sites for groundwater abstraction where the sedimentary fills are sandy. Similarly, the presence of magnetic lineaments in parts of the transition zones suggests the occurrence of fractured basement rocks which are known to be good prospects for groundwater. Basement highs, on the other hand, are usually characterized by impervious rocks of poor aquifer qualities and are responsible for the failure of most of the water boreholes in these zones. Furthermore, the irregular bedrock relief with associated basement highs, depressions, and lineaments that characterize the study area's contact zone would pose a serious engineering problem to the foundation of pavement structures and consequential threat to durability and service life of highways founded in these zones. Therefore, a more site-specific geoelectrical resistivity survey is recommended before drilling boreholes in these zones. Also, thorough geotechnical evaluation of sites found in such geological contact zones is paramount to forestall the failure of structures.

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