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Investigation of Geological Structures of Hydrogeological Importance of 1:100,000 Sheet 185 (Paiko) North-Central Nigeria Using Integrated Geophysical and Remote Sensing Techniques

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ABSTRACT

Aeromagnetic data coupled with Landsat ETM+ data and SRTM DEM have been processed in order to map regional hydrogeological structures in the basement complex region of Paiko, north-central Nigeria. Lineaments were extracted from derivative maps from aeromagnetic, Landsat ETM+ and SRTM DEM datasets. Ground geophysical investigation utilizing Radial Vertical Electrical Sounding (RVES) was established in nine transects comprising of four sounding stations which are oriented in three azimuths. Source Parameter Imaging (SPI) was employed to map the average depths structures from aeromagnetic dataset. Selected thematic layers which included lineaments density, lithologic, slope, drainage density and geomorphologic maps were integrated and modelled using ArcGIS to generate groundwater potential map of the area. Groundwater zones were classified into four categories: very good, good, moderate and poor according to their potential to yield sustainable water to drilled wells. Results from RVES survey reveal a close correlation to lineaments delineated from surface structural mapping and remotely sensed datasets. Hydrogeological significance of these orientations suggest that aeromagnetic data can be used to map relatively deep-seated fractures which are likely to be open groundwater conduits while remotely sensed lineaments and orientations delineated from the RVES survey may indicate areas of recharge. Regions with high lineament density have relatively better groundwater potential. This is attributable to areas having deep weathering profiles associated with intrusive bodies that have resulted in intense fracturing in the area. Drill depths in this area should target a minimum of 80 m to ensure sufficient and sustainable supplies to drilled wells. The outcome of this study should act as information framework that would guide the siting of productive water wells and while providing needed information for relevant agencies in need of data for the development of groundwater resources.

Keywords: groundwater; hydrogeological structures; remote sensing; aeromagnetic survey; radial vertical electrical sounding

1. INTRODUCTION

The occurrence and movement of groundwater is governed mainly by porosity and permeability of a rock formation. In crystalline rocks, there exists an irregularity in the movement of groundwater due to its variable subsurface geology and complex hydrogeology. This in part is due to the fact that groundwater occurrence and accumulation in crystalline terrain is controlled by secondary porosities developed as a result of weathering, jointing and fracturing. Field experience has revealed that in crystalline rock terrains, boreholes have exhibited variable yields even at short distances apart. Major targets in regional groundwater exploration surveys in crystalline basement terrains occur in areas having weathering of considerable thickness and/or where fracturing and jointing are preponderant [1], [2], [3]. Geological fieldwork required in traditional structural mapping can be time-ineffective and limited in operations scope by environmental issues comprising thick vegetation, rugged topography and local social unrest. Remote sensing techniques circumvent these limitations to provide time-effective capture of attributes that may reveal regional geological structures [4], [5], [6], [7], [8]. Lineaments are

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readily observable on aerial photographs, satellite imagery and airborne geophysical data. Lineaments derived from geophysical and RS data have been shown to correlate well with structural discontinuities found in the field [9], [2].

Fractures inferred from both aerogeophysical and remote sensing data are usually verified by surface structural mapping and ground geophysical methods in groundwater exploration because inferred fractures may not always be water bearing. One of such ground geophysical techniques is Radial Vertical Electrical Sounding (RVES). RVES is a modified resistivity technique wherein the magnitude, intensity, and direction of electrical anisotropy are determined. This method has proved very successful in the delineation of subsurface geology and structures, especially for effective identification, behaviour and delineation of fracture orientations in the shallow subsurface of crystalline basement terrains [10], [11], [12], [2].

Communities within the Basement Complex terrains commonly suffer acute potable water shortages arising from the complex hydrogeological setting of the terrain [13], [14]. The poor success rate of water borehole drilling in the Basement Complex regions can be attributed to non-incorporation of hydrogeological concepts into the VES anomaly interpretations in borehole siting [15].
Improving the success rates in such low porosity aquifers requires the interpretation of complimentary geophysical datasets that can image fracture and fault networks. Hence, this study attempts to delineate hydrogeologically significant structures in Paiko region, North-Central Nigeria via the integration of field geological, Landsat, airborne and surface geophysical data. The objectives of this paper are: i). To employ enhanced Landsat ETM+, Shuttle Radar Topographic Mission Digital Elevation Model (SRTM DEM), aeromagnetic data and RVES for the purpose of producing thematic maps of lithology, lineaments, slope, drainage density and geomorphology. ii). To infer deep-seated and shallow depths to lineaments of hydrogeologic significance. iii). To model groundwater potential zones from integrated analysis of the various thematic maps. The groundwater potential map is then correlated with existing boreholes and wells to study the relationship between thematic maps and groundwater yield of the study area.

The outcome of this research would constitute an information framework that would guide the siting of productive water wells and provide baseline information for relevant agencies or the private sector in need of data for the development of groundwater resources and other associated environmental projects.

1.1 Study area description

The study area, which completely covers Paiko Sheet 185, lies between latitudes 9°00′ N and 9°30′ N and longitudes 6°30′ E and 7°00′ E (Figure 1). The study area generally slopes south-west from regions underlain by the basement complex rocks to the area covered by sedimentary rocks. The eastern half of the sheet is rugged country with several peaks formed by granitic and migmatitic rocks. The highest point, which lies within the Fuka hills, stands above 600 m above sea level and about 300 m above the surrounding country. The sedimentary areas in the southwest are flat and low-lying. The area is drained mainly by River Gurara. The tributaries of the river system include rivers Gudna, Jedna, Jednadalaso, Kudan and Jatau. Some of the smaller rivers dry up during the dry seasons between November and April. As a result, the rural dwellers have had to depend on shallow hand-dug wells or pits dug into stream beds for water. Indeed, the settlement patterns in the area have been largely determined by the availability of water in both the sedimentary and basement areas. The drainage of the area is lithologically and structurally controlled [16]. Paiko Sheet 185 falls within the guinea savannah vegetation zone. There are two seasons associated with the climate. These include the rainy and dry seasons. The total annual rainfall in this area is between 1270 mm and 1524 mm, spread over the month of April to October.

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1.2 Geology of study area

The study area lies within the Basement Complex Terrain of Nigeria. The Nigerian Basement Complex forms part of reworked part of the West African Craton underlies about 60% of Nigeria's land mass [17]. The Basement complex has been described by Rahaman (1988), as a heterogeneous assemblage, which include migmatites, gneisses, schists and a series of basic to ultrabasic metamorphosed rocks. Pan African Granites and other minor intrusions such as pegmatite and Aplites dykes and veins, quartz veins have intruded these rocksAbout 15% of the area in the south-western part is covered by sedimentary rocks made up of sandstones while alluvial deposits of gravel, coarse and fine sand, silt and clay are found in the central part of the area (Figure 1).

The structural elements in the study area include joints, faults, foliations and minor folds. Most of these structural elements do not appear on the map due to the scale of the map. Some of the fault lines that appear on the map are deep seated in origin and ancient in age and was as a result of thermotectonic deformational events mostly of the Eburnean and Pan-African Orogeny [18]. The dominant structural trend in the basement is essentially NE-SW and follows the tectonic grain of the schist belt [2], [19]. Subordinate directions, which are locally dominant, include E-W and NW-SE. Widespread fracturing occurs throughout the area and follows the orientation of the major faults.

Information from fieldwork established that the area suffers from chronic water shortage as a consequence of the seasonal nature of the streams and hand-dug wells which dry up during the dry seasons. Boreholes, when available, are poorly developed and have extremely low yields or are completely unproductive.

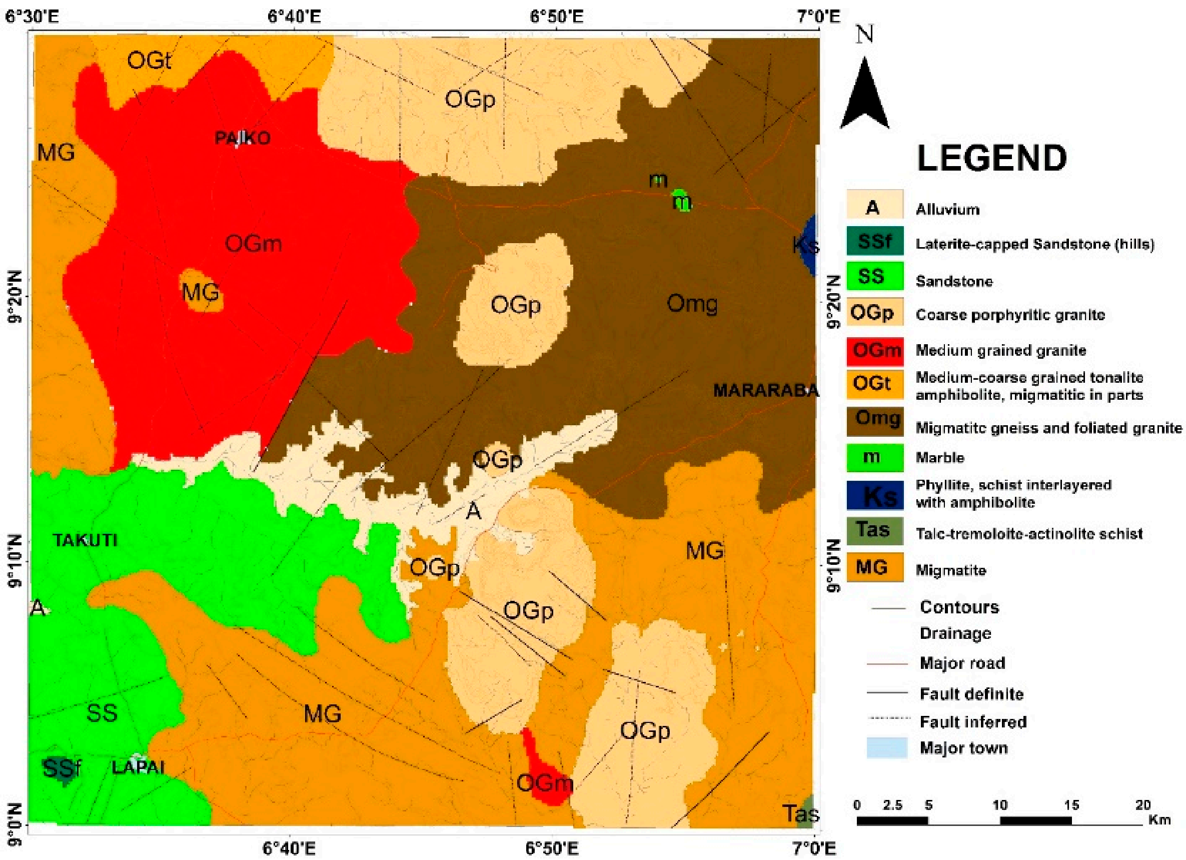

Figure 1: Geological map of Paiko Sheet 185 North-Central Nigeria. Fault lines are digitized from published geologic map and field mapping. (Source: Nigerian Geological Survey Agency (NGSA), 2009)

2 METHODS

Integrating aeromagnetic data and Landsat imagery in groundwater exploration is an established practice in some parts of the world [20], [21]. In central Nigeria, integration of different datasets for groundwater exploration is not very common except for studies performed by [22] who incorporated both Landsat and aeromagnetic analysis in appraising the structural geology of Kakuri, central Nigeria and [23] who used the same method for groundwater exploration. Hence, the methodologies applied in their studies have been adopted and built upon in this study. Processing of Landsat ETM+, SRTM DEM, aeromagnetic, surface structural and RVES datasets reveal anomalies that are employed in delineating features and aquifers that may impact the accumulation and flow of groundwater.

2.1 Lithologic and surface structural data

Field geologic mapping was conducted on a scale of 1:12,500 in the north-western quadrant of the Sheet. In order to assess the hydrogeological conditions of selected boreholes and hand-dug wells, existing wells were investigated with regard to geographic location, rock type, weathering, topography and structure. Structural measurements of joint and fracture sets were taken where possible. Rose diagram showing the predominant joint directions were constructed from these measurements.

2.2 Remote sensing data processing

Image processing for both Landsat ETM+ and SRTM DEM was performed using a combination of ENVI software (ITT Visual Image Solutions) and ArcGIS software (Environmental Systems Research Institute). Shaded relief representations of SRTM DEM were applied to enhance terrain features that will aid in lineament extraction. The SRTM DEM was digitally processed to produce thematic layers that include geomorphologic and slope maps. Drainage networks were extracted using the spatial analyst tool of ArcGIS. Drainage density map delineation was carried out by dividing the study area into micro-watersheds using the methods of [24]. Intersection of micro-watersheds and drainage layer was used for the calculation of drainage density for each of the micro-watershed expressed in terms of the length of channels per unit area (km/km^2) in the ArcGIS software using a search radius of 2 km. Higher search radii gave rise to drainage densities that are not representative of the drainage networks in the area. The drainage density values thus obtained were reclassified to prepare a drainage density map of the study area.

Landsat Enhanced Thematic Mapper (ETM+) 7 (28.5 m resolution) path/row (189/054) was acquired February, 2013. Pre-processing and processing of Landsat images included layer stacking, optimum index factor (OIF) calculations, band combination and principal component analysis (PCA). Contrast stretching and edge enhancement using the Sobel edge detector algorithm were also applied to the Band 5 image in order to enhance mapping of linear structures. For other features like contact locations and lithologic discrimination, PCA worked better as spectral responses are important in this regard. Lineaments were digitised separately from SRTM DEM and Landsat derived maps and subsequently combined to form a composite of lineaments extracted from remote sensing imagery.

2.3 Aeromagnetic Data Processing

The aeromagnetic data was obtained from NGSA. The data was acquired along a series of NE-SW direction with a flight line spacing of 500 m and terrain clearance of 80 m. The average magnetic inclination and declination across the survey is -5.49° and -1.99° respectively. The data was gridded using the minimum curvature gridding method [25]. The total magnetic intensity field has been IGRF (International Geomagnetic Reference Field, 2009) corrected and super-regional field of 32000nT was deducted from the raw data. The airborne magnetic data were processed in Oasis montaj software, while information extraction and interpretation was done using ArcGIS software. The magnetic data was initially subjected to Reduction

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to the Magnetic Equator (RTE) and was further processed to investigate the presence of buried structures that might be relevant in groundwater exploration. Directional and normalised derivatives were calculated to accentuate near surface structures from which lineaments were identified and delineated. These included shaded relief, First vertical, total horizontal, tilt derivatives and analytic signal maps. These maps show delineated lineaments of relatively shallow features important for groundwater evaluation (about 100 m) [26], [27].

Magnetic lineaments can be related to faults and fractures or lithologic contacts. Several geologic processes may change the magnetic properties of the bedrock depending on prevailing physical and chemical conditions and mineralogy [28]. Hence, faults and fractures may induce a magnetic minimum or maximum. After series of interpretation, magnetic minima were found to be more representative of faults and fractures. A composite of all magnetic lineaments and its corresponding rose diagram was constructed. Finally, composite lineament map from different data sources were integrated to form a final lineament map of the study area. Subsequently, a lineament density

Table 1: Assigned classes of the features of the thematic maps used to model groundwater potentials in the study area using ArcGIS weighted overlay tool.

Thematic maps	Assigned classes	Criteria
Lithology	1	Alluvium
	2	Sandstone
	3	Gneiss
	4	Migmatite
	5	Granite
Lineament density	1	0 - 0.5 km/km^2
	2	0.5 - 1.0 km/km^2
	3	1.0 – 1.50 km/km^2
	4	1.5-2.0 km/km^2
	5	2.0 – 2.5 km/km2
Geomorphology	1	Peak
	2	Ridge
	3	Pass
	4	Plain
	5	Channel
Slope	1	21.6 - 66.5
	2	11.6 - 21.5
	3	5.6 – 11.5
	4	2.1 - 5.5
	5	0 - 2
Drainage density	1	0 - 0.5 km/km^2
	2	0.51 - 0.6 km/km^2
	3	0.66 – 0.85 km/km^2
	4	0.86 - 1.15 km/km^2
	5	1.16 – 1.75 km/km2

map was created using the line density tool of ArcGIS with search radius of 2 km. Source Parameter Imaging algorithm (local wave number) [29] was applied to the RTE magnetic data to model depth to causative bodies.

2.4 GIS Modelling

In the exploration of groundwater, especially at regional scales, there are lots of criteria to select from that control the availability of groundwater in particular terrains. Selection criteria for optimum groundwater

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development site are highly subjective. As the number of criteria to be considered keep increasing, the task of objectively and optimally selecting a site becomes increasingly complex. A mathematical approach for the decision-support tool capable of solving complex decision problems [30].

The AHP is a powerful tool capable of considering an unlimited number of significant criteria exhibiting different units or no units at all.

Selected thematic layers were assigned weights using AHP excel template [31] according to their importance in groundwater availability. Thereafter, these thematic layers were reclassified to a common scale of 1 to 5 by intervals of 1, called scale values for the weighted overlay operation, with 5 being the highest potentiality score, 1 being the lowest and 0 being restricted (unsuitable) values (Table 1). The ArcGIS Weighted Overlay tool requires integers for the scale values, which were calculated by multiplying the weighted values by 5 and rounding to the nearest integer. These scale values were used as the potentiality scores (Figure 2).

Matrix		LITHOLOGY 1	LINEAMENT DENSITY 2	GEOMORPHOLOGY 3	SLOPE 4	DRAINAGE DENSITY 5	0 6	0 7	0 8	0 9	0 10	normalized principal Eigenvector
LITHOLOGY	1	-	2	4	7	9	-	-	-	-	-	46.85%
LINEAMENT DENSITY	2	1/2	-	3	5	7	-	-	-	-	-	29.77%
GEOMORPHOLOGY	3	1/4	1/3	-	2	5	-	-	-	-	-	13.09%
SLOPE	4	1/7	1/5	1/2	-	2	-	-	-	-	-	6.53%
DRAINAGE DENSITY	5	1/9	1/7	1/5	1/2	-	-	-	-	-	-	3.76%

Figure 2: Analytic Hierarchy Process (AHP) excel template showing pair-wise comparison matrix table of the different thematic layers.

2.5 Ground geophysical survey

The essence of conducting surface structural mapping is to understand the relationship between exposed fractures on outcrops and their behaviour in the subsurface. However, inferences made about the surface fractures in relation to their subsurface behaviours are always met with high uncertainties. Therefore, to greatly minimise these uncertainties, Radial Vertical Electrical Sounding (RVES) is employed to aid the understanding of the behaviour of crystalline rock structures at depth. The interpreted RVES data is used to correlate the general fracture trends of the rocks from surface geology, with those determined by RVES method.

Rock formations which are anisotropic due to the presence of fractures, have shown that the apparent resistivity ρt, measured normal to its strike direction, is less than ρs, measured along the strike direction, although the true resistivity ρt, normal to its stratification, is greater than that parallel to the plane of stratification, ps. This is called the 'paradox of anisotropy' [32].

In this study, RVES have been conducted at selected sites using Schlumberger configuration (AB/2=100 m). The apparent resistivities are measured along three different azimuths N-S, NE-SW and NW-SE for a given AB/2 separation and are plotted resulting in an electrical anisotropy polygon. For an isotropic homogeneous formation, this electrical anisotropy polygon will assume a circular shape. Any deviation from a circle to an ellipse is indicative of anisotropic nature of the formation. The major axis of the ellipse which can fit any such anisotropy polygon gives the strike direction

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of the fracture. A high ratio of the long to short axis is indication of the presence of fractures (faults and joints system) in an area. If it is low, fractures are not significant or are absent.

The coefficient of apparent anisotropy λ_a (degree of fracturing) is calculated from each anisotropy ellipse using the relationship, λ_a, = *a/b,* where a and *b are* the semi-major and semi-minor axes of the ellipse. All the calculated λ_a, values are then plotted against the corresponding AB/2 separations. The behaviour of rock fracturing at various depths equivalent to different AB/2 separations can thus be understood qualitatively from the variation of λ_a.

3. RESULTS

3.1 Lithologic and structural mapping

Exposed lithologic units comprised alluvial deposits, granite, gneiss and migmatite. Alluvial deposit occupies streambeds and stream banks. It mainly consist of sand, silt, clay in various proportions with some pebbles and cobbles and the colour varies from greyish white through reddish brown to black. There is a variation in the height of the outcrops which range from steep hills to low lying massive stock with gentle elevations and textures ranging from fine to coarse. Migmatites, which are the most widespread lithology within the study area, outcrop as low lying terrains. Gneisses occur as a group of minor discontinuous intrusions of small area extent in the migmatites. Granitic rocks outcrop mainly as high, extensive whalebacks. They form the highest elevation in the area. Foliations in the gneisses gave dominant general trend of NW-SE and NE-SW. Transcurrent fault sets were observed in the area. Fault axis of 040^0 - 060° were measured in the granites. The principal joint directions trend NW-SE. Minor joint directions trend NE-SW (Figure 3).

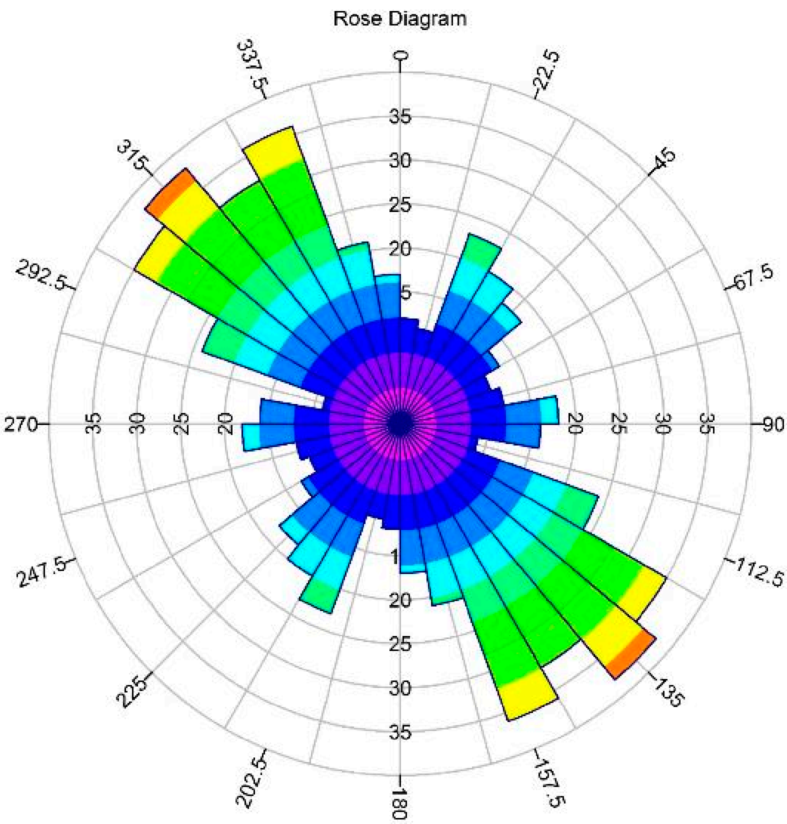

Figure 3: Generalised Rose Plot showing trends of joints on exposed rock surfaces in the study area.

3.2 Drainage networks density

The drainage system of the area exhibits dendritic drainage, typical of a crystalline basement terrain. Spatial distribution of drainage density is shown in (Figure 5). The area has moderately dense drainage system with values ranging from 0.5 km/km^2 to 1.75

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km/km^2. Higher drainage densities are found concentrated in central and southern-eastern part of the area due to higher surface water runoff. These values imply that recharge and percolation into the subsurface is low. Therefore, in using this thematic map for the GIS modelling, drainage density was assigned a low weight because of its minimal contribution to the groundwater potential of the area.

3.3 Lineaments and lineament density maps

The lineaments extracted from remotely sensed imagery are oriented principally in the NW-SE to NE-SW directions (Figure 6). These lineaments directions correlate well with joint directions mapped on the surface. In addition, these lineaments to correspond to alignment of the stream segments implying a form of structural control of the drainage system. Magnetic lineaments extracted from aeromagnetic data trend principally in the ENE-WSW to ESE-WNW directions (Figure 4). These faults/fractures are attributable to deep seated structures [33] of the oldest fault/fractures formed during the initial tectonic processes of the region which exerted strong controls the overall fracture orientation. The NW-SE structures are related to the structural fabrics of the Cretaceous Bida Basin, while the NE-SW trending structures are parallel to the Pan-African regional tectonics. This deformation event is closely related to the formation of the schist belts and mylonites in the region. [34] have attributed NE-SW trend to the landward extension of the Chain and Romanche Fracture Zones from the Atlantic Ocean [38].

It is clear that magnetic lineaments and remotely sensed lineaments have made different contributions towards groundwater availability in the area. AM data has been used to map deep fractures and intrusive bodies under weathered zones. These areas are likely to be open groundwater conduits. The remotely sensed data have delineated lineaments that most likely represents recharge areas.

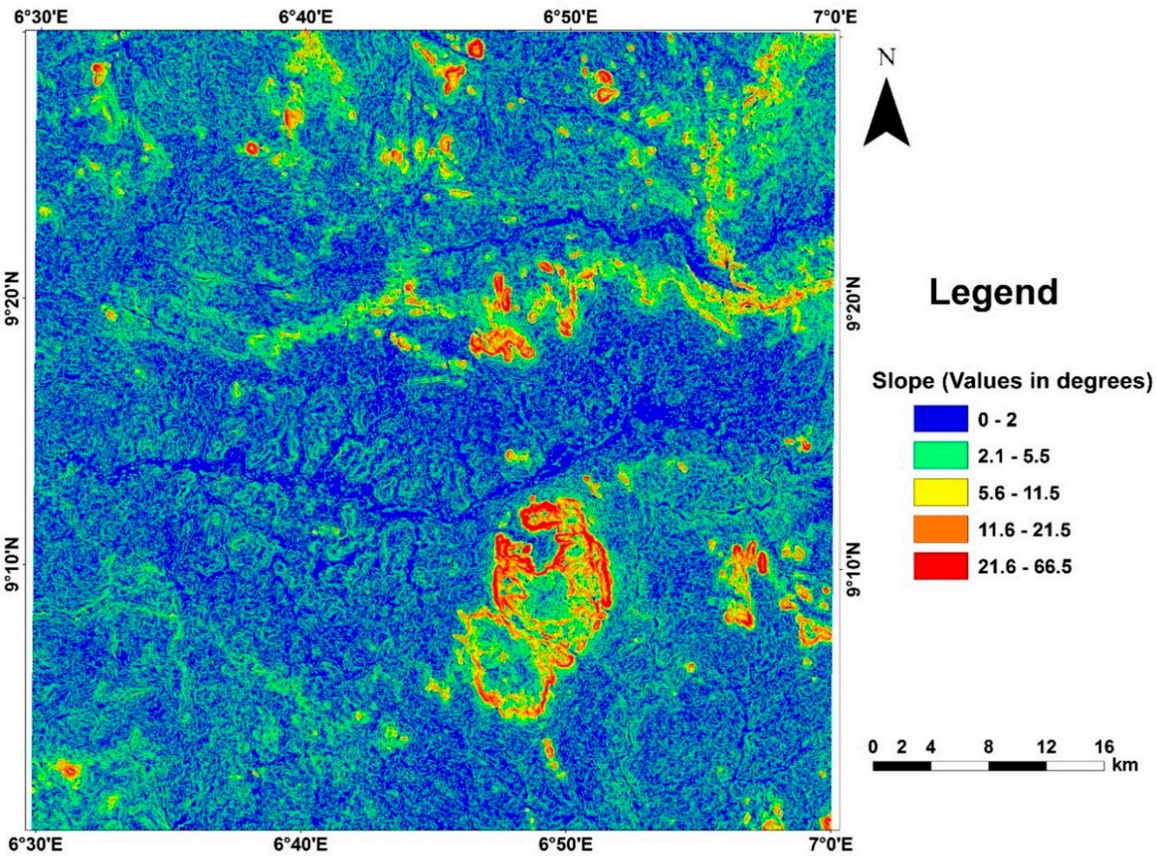

Figure 4: Slope map of Paiko Sheet 185 North-Central Nigeria produced from SRTM DEM using the spatial analyst extension of ArcGIS. Low slope angles are representative of areas that encourage infiltration of rainfall, thus enhancing groundwater potential of the area.

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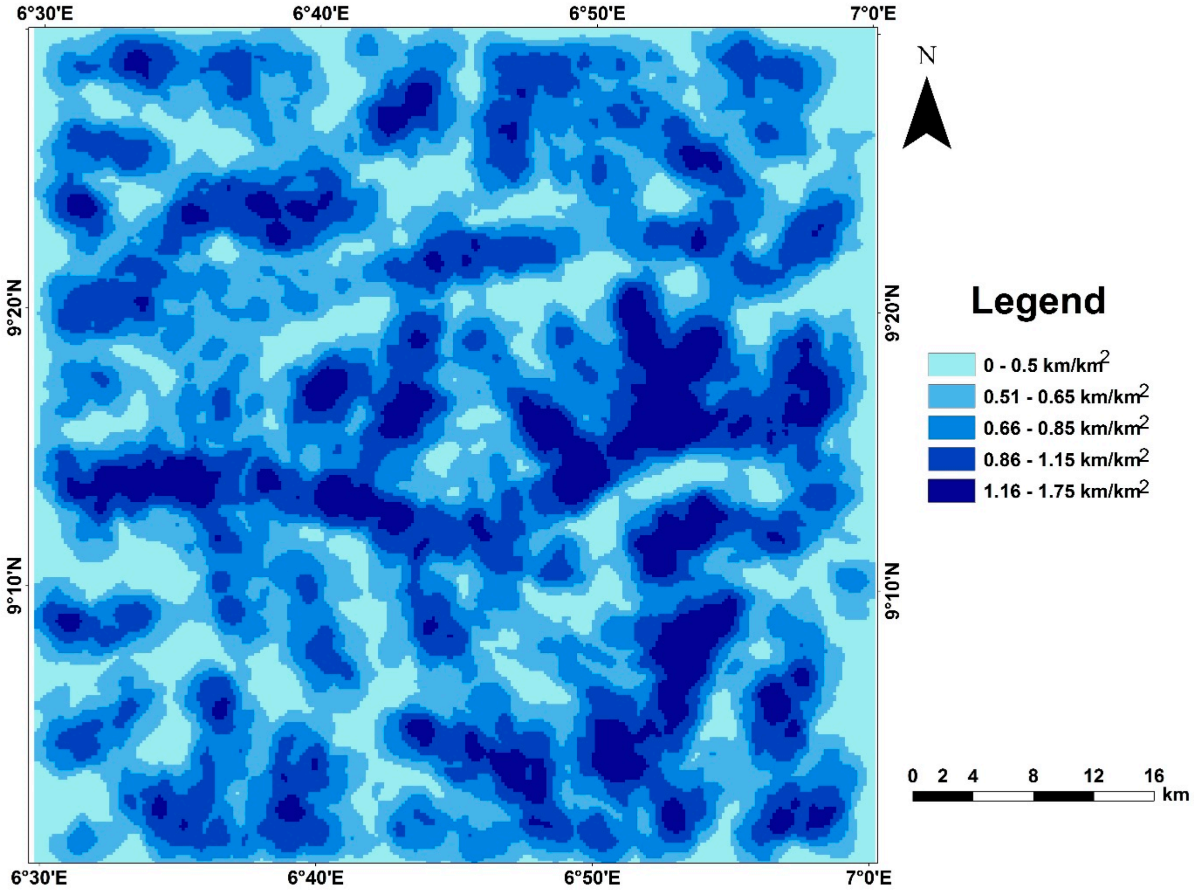

Figure 5: Drainage networks density of Paiko Sheet 185 North-Central Nigeria produced from drainage networks extracted from SRTM DEM using density tool of ArcGIS. Areas having lighter shades represents areas of low drainage densities. Drainage density values are inversely proportional to their groundwater recharge potentials.

A composite of all extracted lineaments which was used to produce the composite lineament map of the study area (Figure 7) reveal that the north-western portion of the map has the highest lineament density. This is due to the intersection of several lineaments oriented in different directions. Areas having high lineament densities are the zones of highest porosity and permeability which in turn have greater chance of accumulating groundwater.

3.4 Hydrogeological model

Geomorphology and slope of the area play an important role in the rates of recharge of aquifers in the groundwater system thus giving an indication of good groundwater prospect of the area. The area is mostly gently sloping. However, in the south-eastern part of the study area, there is an increase in slope (Figure 4). The wide range and distribution of the slope values in the study area is typical of crystalline basement terrain. The sedimentary part of the area is generally gently sloping except for few scattered mesas which have relatively high slope. This is also the reason why groundwater potential varies significantly in basement complex terrains. In areas of low slope values, the surface runoff is low allowing more time for infiltration of rainwater, while high slope values enhance runoff and shorten residence time for infiltration and recharge. In reclassifying the slope angle thematic map, low classes were assigned to higher slope angles because higher slope angles impact negatively on infiltration and groundwater recharge [35].

Geomorphological units like peaks and ridges form inclined erosion surfaces that slope away from the highland fronts and are typically formed by running

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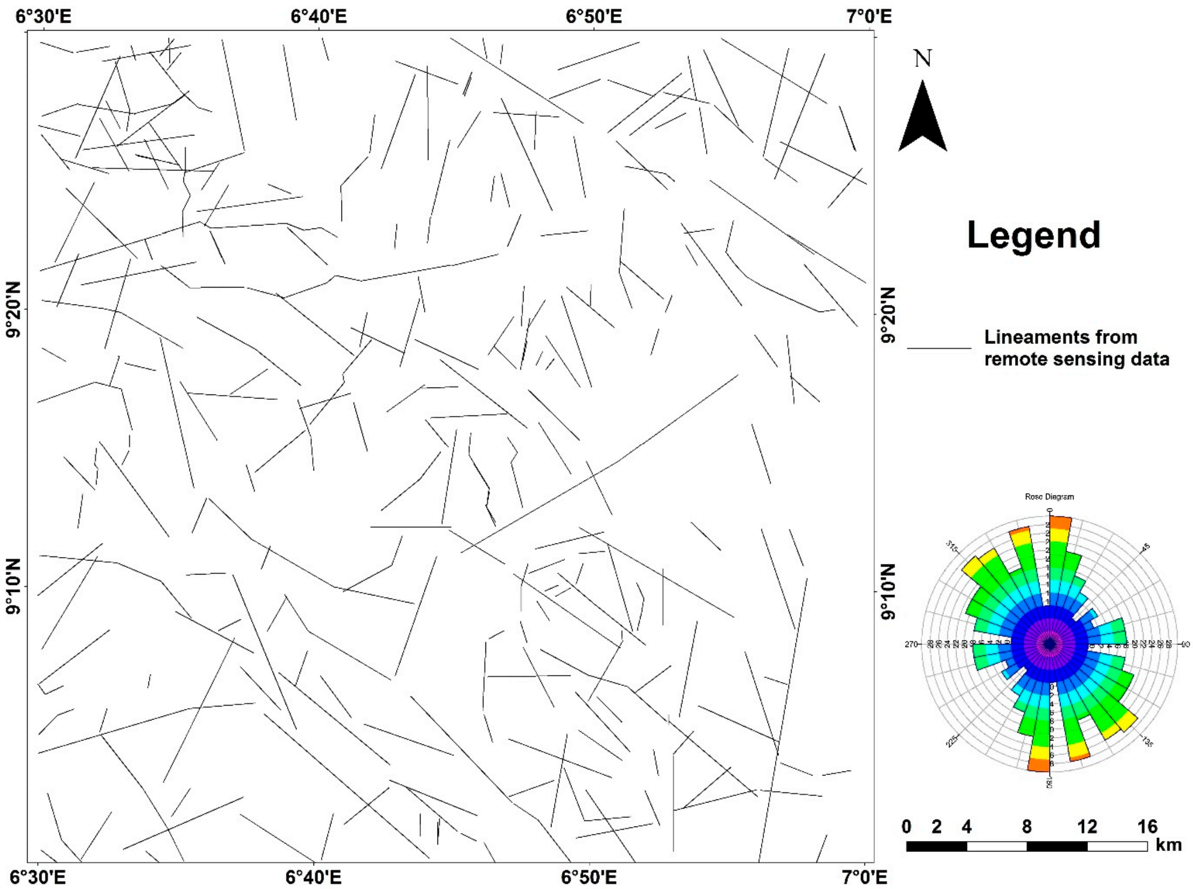

Figure 6: Lineaments extracted from edge enhanced Band 5 of Landsat ETM+ and SRTM DEM of Paiko Sheet 185 North-Central Nigeria. Rosette diagram show lineaments trending principally in the NW-SE and NE-SW directions. Inset: Rosette diagram showing principal orientations of lineaments in the NE-SW and NW-SE directions.

water. The bedrock in the passes may be exposed or thinly covered with alluvium and soils. In the alluvium, they represent different channels with alluvial deposits. The planes and channels are flat to gently sloping topographic features. These support percolation of rainwater and hence promote groundwater accumulation. Deep weathering of crystalline rock formations produced laterites during periods of quite tectonic activities. Some of the lateritic planes form isolated patches at the peaks of the crystalline rocks. The presence of ridges, peaks and other elevated areas, favour loss of water and hence, not favourable for groundwater accumulation.

3.5 Depth modelling using Source Parameter Imaging (SPI)

The basis for using SPI to determine magnetic source depths is to create a database for every 250 X 250 km^2 The SPI depth range from 100 m to 3000 m. It should be noted that only shallow depths of not greater than 150 m is considered adequate for exploration of groundwater in this area. The depth of causative sources as interpreted from the Source Parameter Imaging (SPI) map show that areas within the crystalline basement are shallower than areas within the sedimentary portion (Figure 8). In places where shallow depths (magenta) were obtained within the sedimentary region may be attributed to intrusive rocks within the formation. Since intersection of fractures aid fracturing, it is expected that that deeper zones especially in the crystalline rock terrains should coincide with high lineament density (Figure 9). These are promising sites for groundwater accumulation. Also, relatively deep sections within the crystalline basement are attributable to areas where deep weathering may have occurred. These areas have considerable contribution to groundwater availability.

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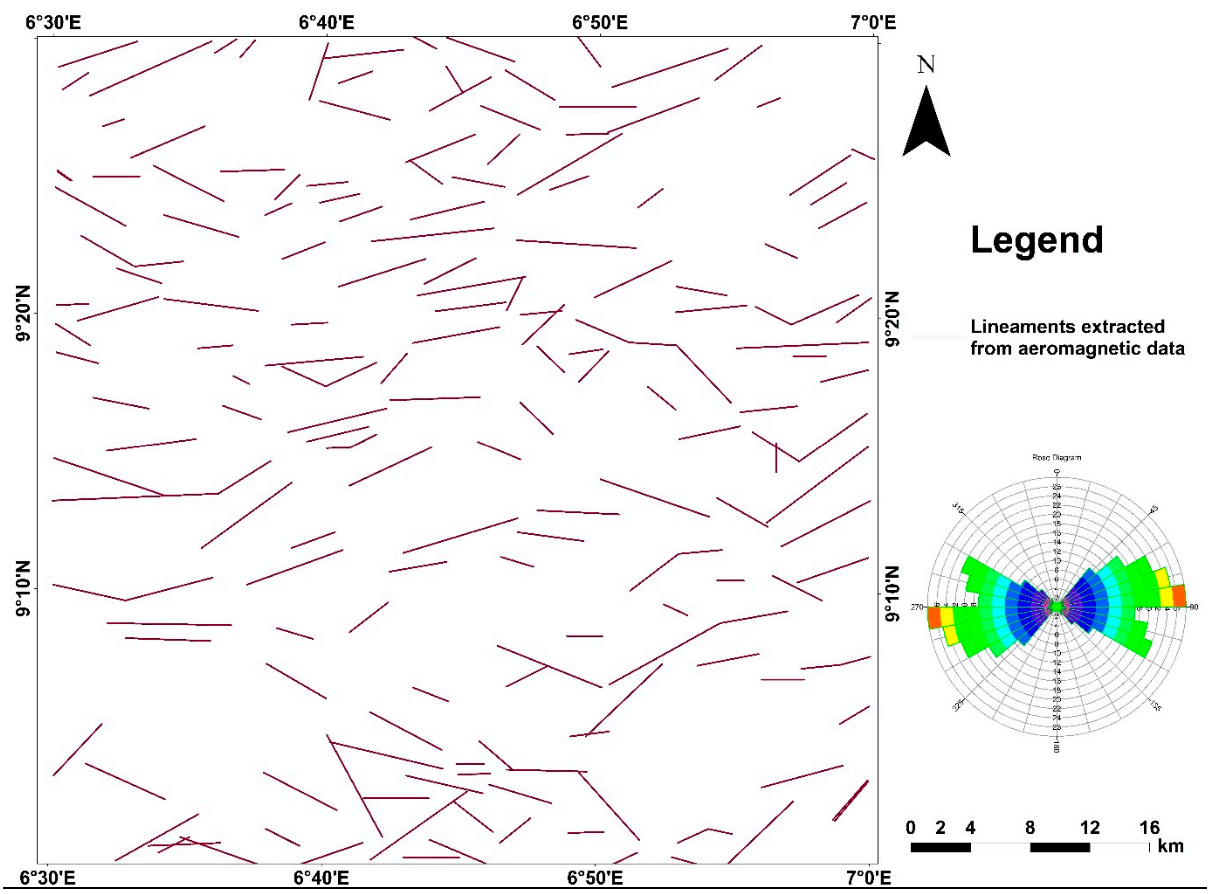

Figure 7: Magnetic lineaments extracted from aeromagnetic data of Paiko Sheet 185 North-Central Nigeria. Lineament map is a composite lineaments extracted from first vertical, horizontal and tilt derivatives of the aeromagnetic data. Inset: Rosette diagram showing principal orientations of lineaments in the ENE-WSW direction.

3.6 Description of electrical Anisotropy polar diagrams and Coefficient of Anisotropy

The inferred structural trends and their corresponding coefficient of anisotropy are presented in Table 4.3. The direction of the electrical anisotropy lies predominantly in the NE-SW directions while others lie in the NW-SE and N-S directions. N-S orientations are predominant at shallow depths especially at the top soil layer. The coefficient of apparent anisotropy values (λa) against various depth equivalents to different AB/2 separations act as an aid to quantitatively understand the behaviour of rock fracturing at various depths. Minor fracturing exists at depths of 30 m – 40 m in all sounding locations. An increase in anisotropy values with depth is common in most of the study area. This increase truncates at approximately AB/2=40 m and subsequently started decreasing from this depth. The decrease of anisotropy at these depths is an indication that fractures are closing up with increasing depth [14]. There exists also fracturing beyond 70 m. This is observable in many sounding stations (Figure 10).

3.7 GIS Modelling

Five groundwater potential zones have been delineated (Very Good, Good, Moderate and Poor and Very poor). The spatial distribution of the various groundwater potential zones are shown in Figure 11. The very good to good zones are spatially distributed in areas where the lithology are most appropriate to have primary porosities (sedimentary sequences in the southwest) or along major lineaments and drainage channels. This underscores the importance of lithology, lineaments and geomorphological units that favour groundwater accumulation in groundwater investigations. Areas with good to moderate groundwater prospectivity are attributed to favourable combinations of the lithology and landform. The poor categories of groundwater potential zones are spatially distributed mainly along ridges and peaks and to a certain extent, zones with low lineament density. Foliated rocks such as migmatite and gneiss are classified as moderate groundwater potential zones. The alluvium that lies at the central portion of the map with the sedimentary rocks in southwest have very good to good groundwater potential. The most promising targets in the alluvium constitute areas with dense lineaments.

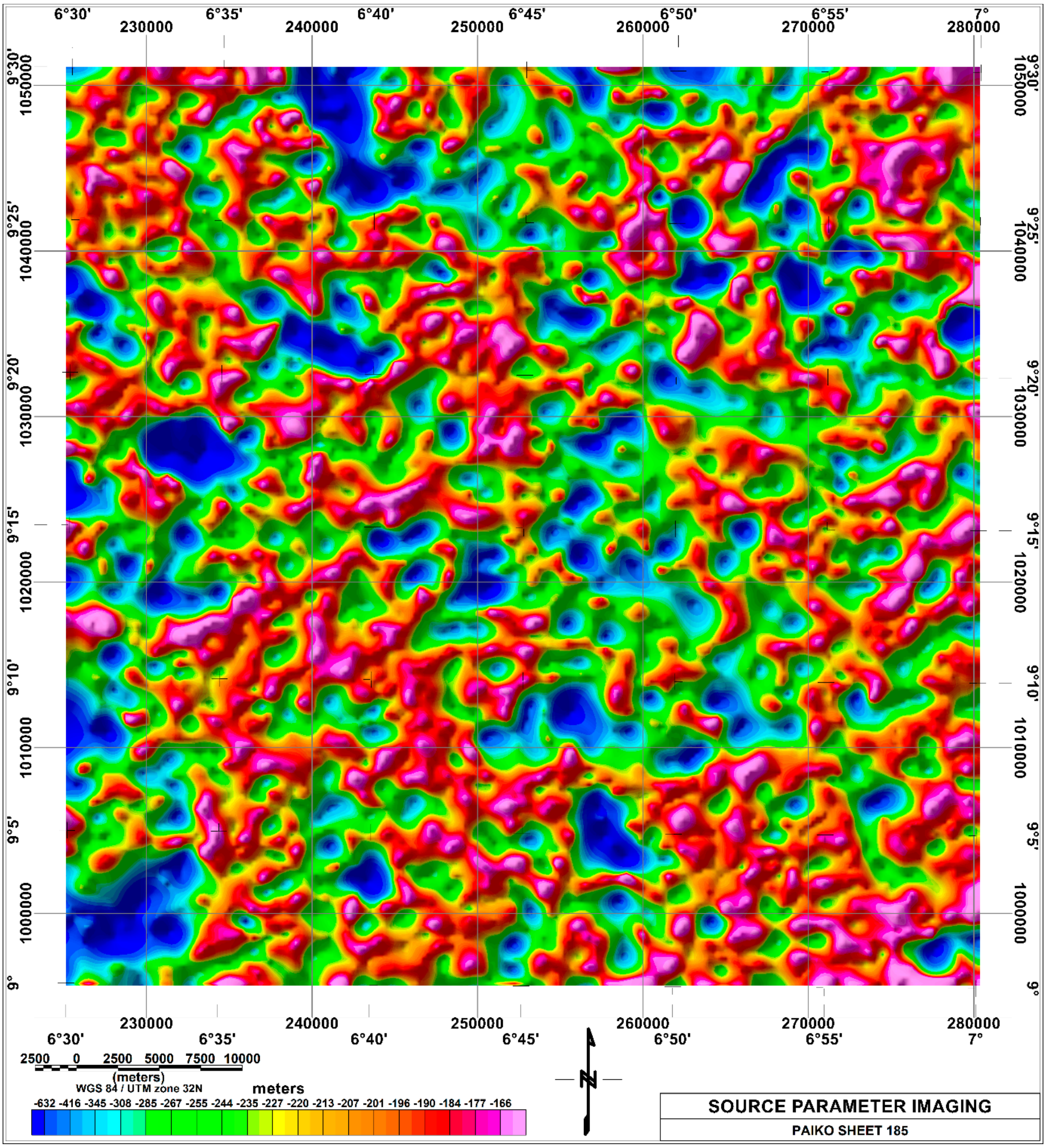

Figure 8: Source Parameter Imaging (SPI) map of Paiko Sheet 185 North-Central Nigeria. Areas with blue colouration are representative of deep magnetic features. Shallow areas in magenta in the sedimentary section are attributable to intrusive
bodies.

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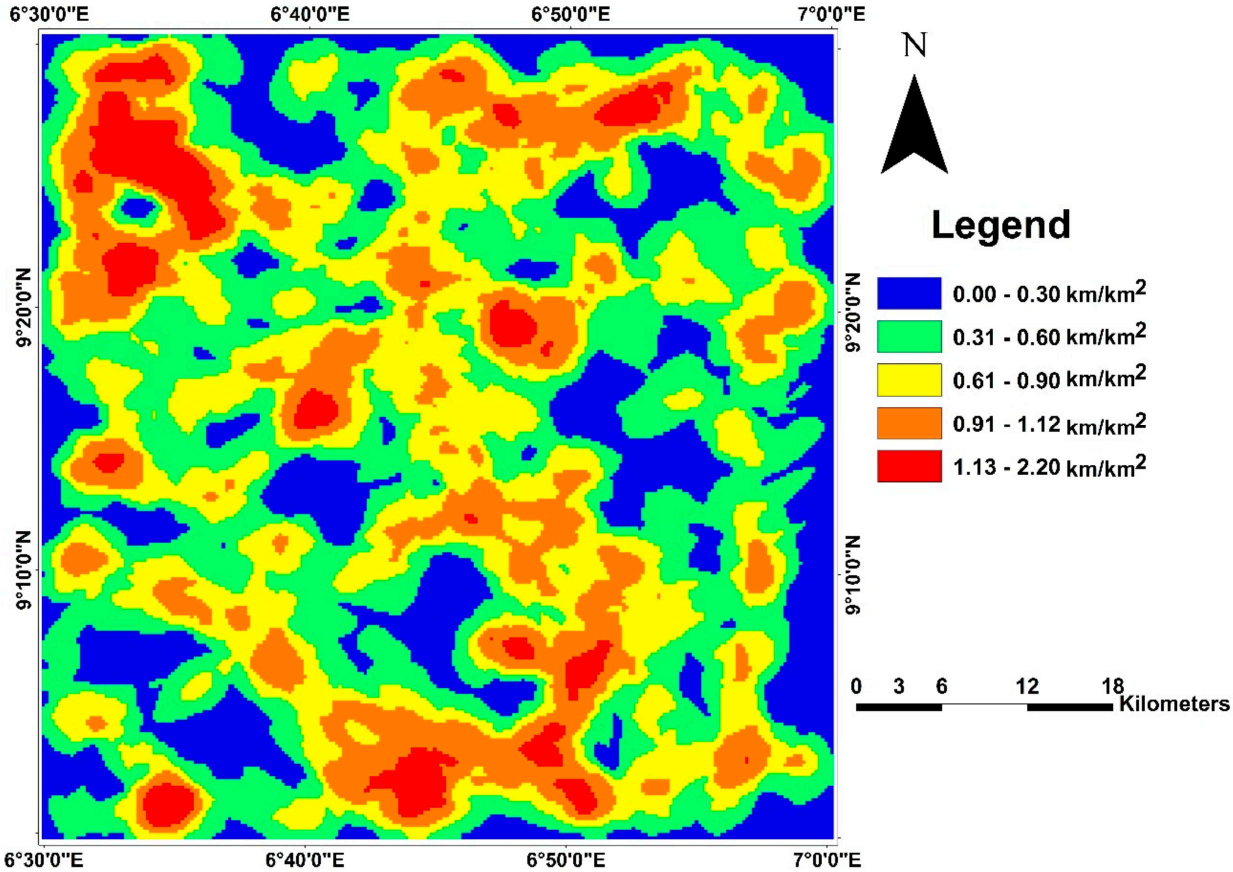
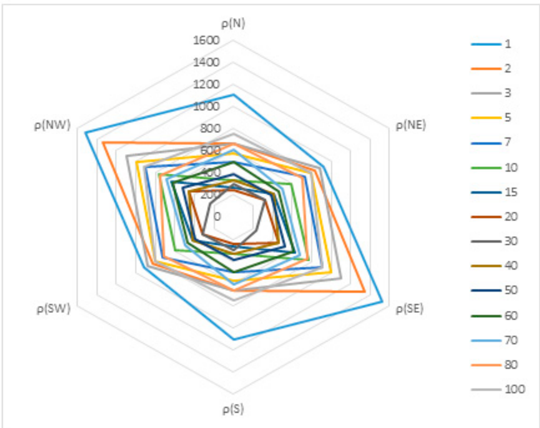
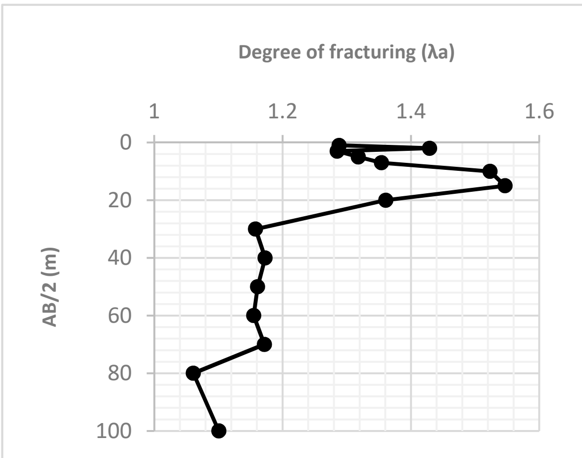


Figure 9: Composite Lineament density map of Paiko Sheet 185 North-Central Nigeria. High lineament densities are shown red, while low lineament density are shown in blue.





(a) (b)

Figure 10: (a) Electrical anisotropy polygon constructed from plots of apparent resistivity along three azimuths. The fracture orientation trend principally in the NE-SW direction. (b) Plot of variation of degree with fracturing. This shows that there is diminution of fracture with depth.

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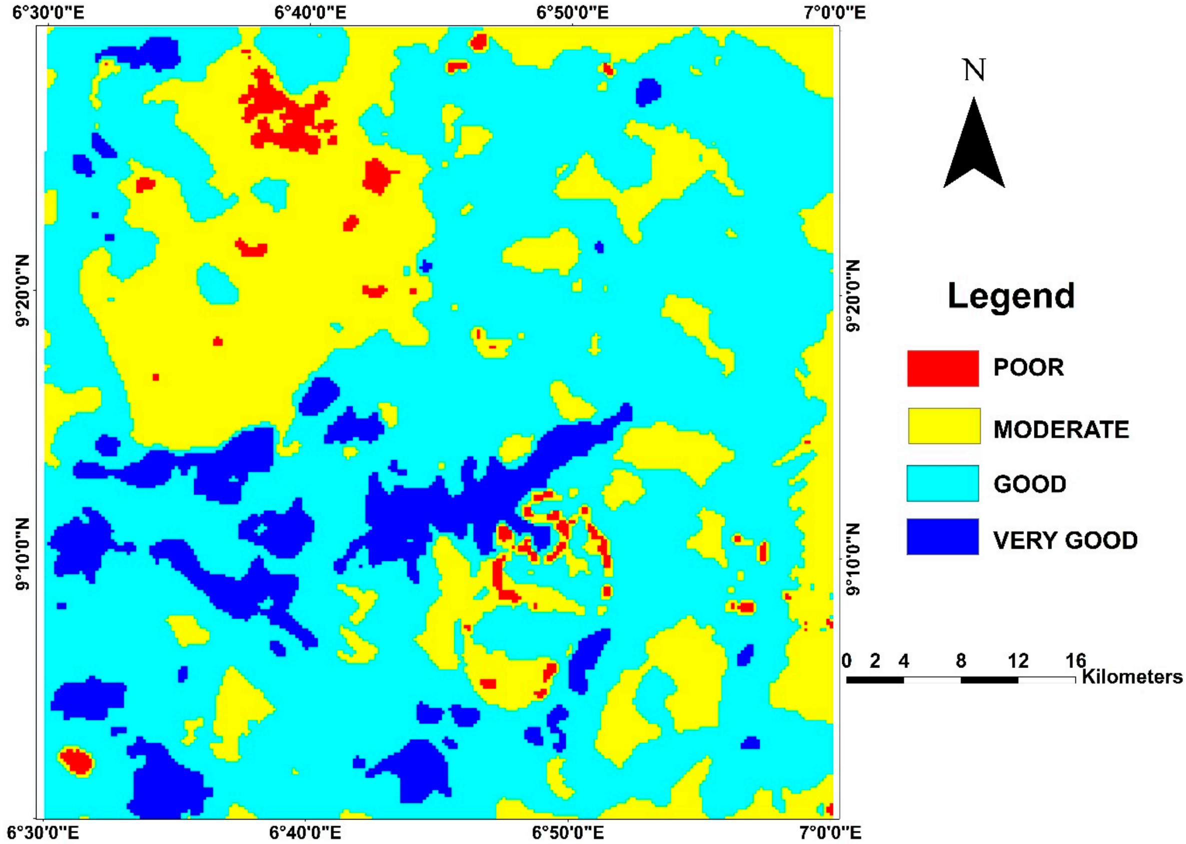

Figure 11: Groundwater Potential map of Paiko Sheet 185 North-Central Nigeria showing four categories of groundwater potential zones. Regions in red show poor groundwater potential zones while areas in blue show very good groundwater potential zones.

4. DISCUSSION

Depths to groundwater level in dug-wells is often very shallow between 3 m and 10 m. Most of these are seasonal because water tapped in these wells are from the shallow weathered residuum. The siting of certain boreholes most times are biased to proximity to settlements and good access for drilling rigs. This indicates that considerations are not given to the factors that affect groundwater availability such as the influence of the structural features and thickness of weathering of the area. This can possibly explain the prevalence of low yields in boreholes as drill depths rarely exceed 60 m. This is collaborated from the results of the RVES as pronounced fracturing occur at depths beyond the depths penetrated by drilled boreholes in the region. Hence, the reason for most failed boreholes as drilled depths were not able to penetrate structures required for the accumulation of groundwater.

Linear structures such as fractures and shear zones that characterise the study area have different orientations. Present are the minor N-S fractures which are attributed to brittle deformation and the twin conjugate sets of NE-SW and NW-SE trends, produced by transcurrent movements (Olasehinde *et al.,* 1990). The age relationships of the conjugate fracture sets cannot be easily resolved from their relative dispositions on the map, but it has been established that NW – SE trending lineaments are analogous to the predominant trend of the Bida Basin. The structural framework of the Nigerian Basement Complex is dominated by the NE – SW lineaments [36], [34]. The ENE-WSW orientation from the AM data arises from an ancient zone of weakness in the basement oriented in the E-W direction that got reactivated during the late Phanerozoic plate tectonic episode [33]. Intersections of AM coupled with RS and RVES will aid the accumulation and flow of groundwater. Relatively flat areas and thickly weathered zones in association with high lineament densities mapped using RS and GIS characterize high groundwater potential zones.

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Validation of the groundwater potential map was done on well data for selected drilled boreholes. Borehole yields range from 50m^3/day to 100m^3/day. On the average, most yield for boreholes are poor. However, higher yields were found in wells drilled at places having intersection of fractures and deeply weathered residuum. Since thickly weathered crystalline rocks favour infiltration and storage of groundwater, their potential to yield higher amounts of water to drilled wells are greatly enhanced especially when this occurs within fractured zones [37]. These areas were clearly demarcated as good groundwater potential areas on the map. It is also pertinent to note that some low yield boreholes in areas otherwise marked good potential were due to drilled wells penetrating only shallow weathered basement or not penetrating fractures at depth.

In the development of groundwater resources in places demarcated as good groundwater potential areas, mitigation efforts should be put in place so as to check possible water quality issues arising from contamination associated with mineralisation in deep water wells in weathered igneous rocks. Although, this phenomenon is not unique only to deep water wells, further work should investigate the likelihood of its occurrence in the area.

In many areas, settlements are not densely populated coupled with a large percentage of the inhabitants' inability to afford motorised boreholes. Hence, it behoves on the government to either subside or take complete responsibility of the drilling projects. However, if these conditions are not met, the inhabitants have to settle for boreholes drilled at relatively shallow depths with the risk of having insufficient water supplies and groundwater contamination.

5. CONCLUSION

Lineament mapping was carried out using Landsat ETM+, SRTM DEM and aeromagnetic datasets by applying various digital image processing techniques which included edge enhancement, shaded relief image representations. Aeromagnetic derivative maps were also utilised. Most of the lineaments were identified using greyscale, shaded relief, digitally processed colour composite images and edge enhancement provided an effective way to detect most remote sensing lineaments. In the airborne magnetic products, the vertical and tilt derivative maps were used to delineate lineaments. Comparison of rose diagrams of principal joint directions and regional lineaments trends show a high correlation with the major linear structures in the study area. High correlation that exist between lineaments delineated from RS and aeromagnetic data, fractures derived from RVES survey and measured joint directions suggest that these features correspond to fracture zones. The accumulation and flow of groundwater is largely controlled by rock type, fractures and slope revealed from GIS analyses and field investigations. In granitic rocks, bedrock fractures and intense fracturing control groundwater flow and storage.

Utilising GIS in groundwater exploration strategies is time and cost-effective and has many advantages over traditional approaches. However; to fully understand the hydrogeological nature of hard rock aquifers, surface lithologic and structural mapping are crucial. Optimum yields to drilled wells are obtainable in areas having deep weathering profiles in association with intense fracturing resulting from intrusive bodies and other related tactic activities. Integration of different data layers in a GIS environment followed by spatial and statistical analysis of the data allowed to understand the correlation between different parameters and unravel the nature of hard rock aquifers. The groundwater potential model derived through integration of thematic maps demonstrates the hydrogeological significance of structure, rock, and landform type. This integrated approach will help to design suitable groundwater exploration plans in the future.

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