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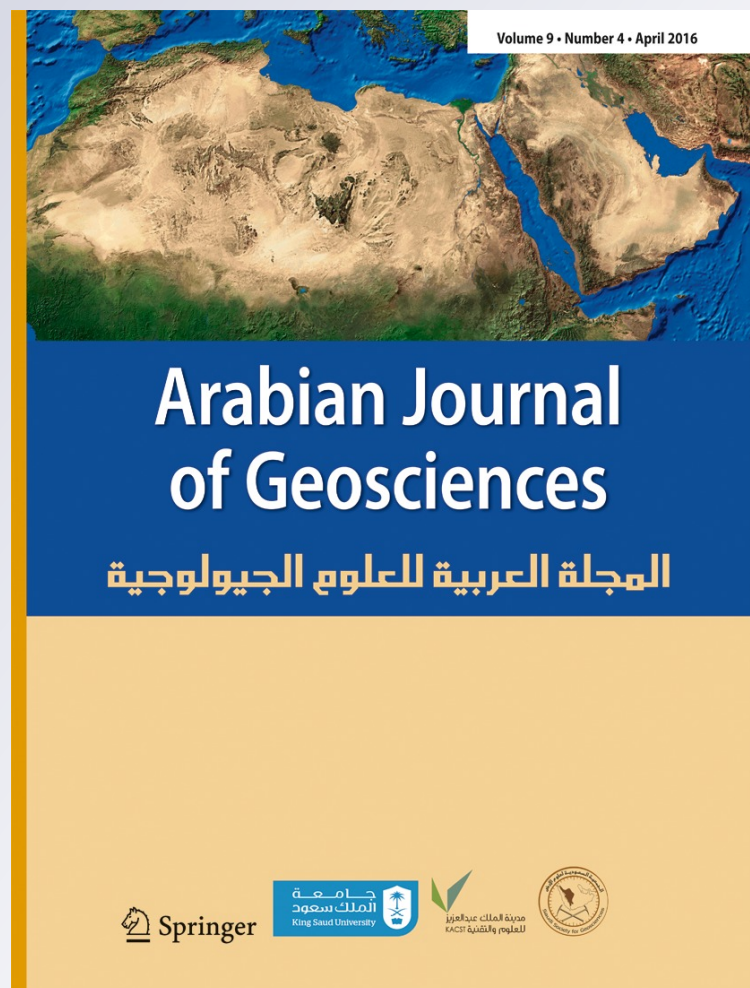
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Application of cross-square array and resistivity anisotropy for fracture detection in crystalline bedrock

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Abstract Azimuthal cross-square array resistivity soundings were used to detect fractures and investigate the anisotropic properties of crystalline basement rocks in some parts of Eruwa, southwestern Nigeria. Resistivity measurements were taken at ten locations using an Ohmega terrameter. The technique involves the rotation of the electrode array in four different azimuths, namely, 0°, 45°, 90°, and 135°, at electrode spacing of $A(2)^{1/2}$. The measured apparent resistivity were used to calculate azimuthal resistivity, fracture strike, bedrock anisotropy, coefficient of anisotropy, secondary porosity, and azimuthal inhomogeneity ratio (AIR). The results showed that the measured apparent resistivity changed with the orientation of the array implying fracture anisotropy in the subsurface. The calculated azimuthal resistivity shows that values increase with electrode spacing with polar plots indicating varied fracture directions. Primary fractures in the study area are oriented dominantly in N-S, NW-SE, and E-W directions which contrast with NE-SW and E-W trends of their secondary counterparts. Few tertiary fractures are aligned in E-W direction. Coefficient of anisotropy (λ) ranges between 1.05 and 3.68, while bedrock anisotropy (N) varies from 1.002 to 2.483; calculated secondary porosity (fracture porosity) ranges from 0.07

to 0.99. The comparison of the fracture porosity and mean resistivity revealed four major fracture zones in the study area. Interpreted AIR (azimuthal resistivity ratio) values of -5.09 to 0.97 show that anisotropy inhomogeneity of the study area is low. This work therefore gives insight to anisotropic properties as well as the fracture characteristics in the study area.

Keywords Azimuth · Cross-square array · Fracture · Anisotropy · Porosity

Introduction

Electrical anisotropy (or inhomogeneity) of crystalline basement is often attributed to structural elements like foliations, joints, and fractures (Billings 1972; Olasehinde and Bayewu 2011; Bayewu et al. 2014; Malik et al. 1983). It has been shown by Odeyemi et al. (1985), Beeson and Jones (1988), Okereke and Esu (1994), and Edet and Essien (1994) that the well yield and its direction flow in fractured rocks are directly related to the density, frequency, orientation, and inter-connection of structural features at depth. One of the primary problems of investigating groundwater potential in crystalline rocks is locating the fracture network (Ajibade et al. 2012). Based on analogy between the Darcy's law and Ohm's law for electric current flow, it is possible to determine the direction of groundwater flow from electrical resistivity measured as a function of azimuth. Therefore, fractures in rocks are important pathways for groundwater flow and contaminant migration. Groundwater flow through a fracture network is strongly influenced by hydraulic anisotropy resulting from the geometry of the fractures, and the preferential strike of fracture sets makes rock to be both electrically and hydraulically anisotropic (Slater et al. 2006). Fractures provide sources of water in bedrock aquifers and are also of great importance to waste disposal, groundwater

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protection, and contaminant transport. The existence of fractures in rocks of low permeability can elevate hydraulic conductivity by several orders of magnitude and generally increase in complexity of groundwater flow (Taylor and Fleming 1988).

The introduction of a comparatively new method such as azimuthal resistivity survey (ARS) is to determine the principal direction of electrical anisotropy and direction of underground water flow in relation to the geology. There has been growing need and interest in the application of ARS using cross-square direct-current resistivity array method to locate, characterize, and identify the directional properties of anisotropic rock mass. Azimuthal resistivity survey using cross-square array is a modified resistivity survey in which the magnitude and direction of electrical anisotropy can be determined (Leonard-Mayer 1984). Different authors have shown the usefulness of azimuthal resistivity survey in determining the principal direction of electrical anisotropy (Taylor and Fleming 1988; Ritzi and Andolsek 1992; Skjerna and Jørgensen 1993; Al Hagrey 1994; Odoh 2010; Ehirim and Essien 2009).

However, in using azimuthal resistivity survey, any observed change in apparent resistivity (ρ_a) is interpreted as an indication of fracture anisotropy, which in most cases might also be produced by the presence of a dipping bed or inhomogeneity or lateral changes in apparent resistivity (Matias and Habberjam 1986; Watson and Barker 1999; Busby 2000). Several authors (Habberjam and Watkins 1967; Taylor and Fleming 1988; Skjerna and Jørgensen 1993; Carlson et al. 1996; Busby 2000; Ramanujam et al. 2006) have worked on the use of different array adaptations in azimuthal resistivity survey to characterize the electrical anisotropy of different rock types in terms of the anisotropic parameters, viz., the direction and coefficient of electrical anisotropy (λ).

The identification and classification of fracture is important in rocks with low primary (or matrix) porosity because the bulk porosity and permeability are determined mainly by the intensity, orientation, connectivity, aperture, and in the fill of fracture systems (Skjerna and Jørgensen 1993; Watson and Baker 1999). The hydraulic conductivity of fracture systems can range over several orders of magnitude.

Geophysical study on the natural fracture system is warranted to improve the understanding of their formation. The determinations of the strength, fracture behavior, and orientation of bedrock fracture are important materials in improving the ability to forecast and to anticipate its severity (Taylor and Fleming 1988).

The study area, Eruwa, is characterized by visible basement rocks and a lot of failed hand-dug wells and boreholes, thereby making the area to suffer from lack of adequate portable water. The successful location of suitable points for groundwater exploitation will be greatly aided by understanding of the anisotropy, directional connectivity, and porosity of the fracture system. This will greatly enhance field deployment during groundwater exploration and help to identify viable aquifer system which is essential for sustainable development of this region.

This research therefore is aimed at detecting fractures, investigating the anisotropic properties of crystalline bedrock, determining the orientation of bedrock fractures and secondary porosity of the rocks in the study area, and delineating the degree of fracturing of the underlying basement with the use of cross-square array direct-current resistivity method. In the study area, ARS method using the cross-square array was used to measure the apparent resistivity of the selected locations, for subsurface condition such as to (a) determine depth-wise fractures in different direction in the subsurface and (b) use RVES direct-current resistivity method to detect fractures in hard rock. The aim in this work is broader when compared to Ajibade et al. (2012), who used this array in determining the fracture direction alone.

Geologic setting

The study area (Fig. 1) is located in Eruwa, one of the ancient and major towns in southwestern part of Nigeria; the area lies within latitude $7^{\circ} 31' \text{ N}$ to $7^{\circ} 34' \text{ N}$ and longitude $3^{\circ} 24' \text{ E}$ to $3^{\circ} 27' \text{ E}$. It is lowland and is basically characterized by an undulating topography with the highest elevation of about 550 m above sea level.

The area falls within the Southwestern Basement Complex of Nigeria, and it is characterized by porphyritic granite, granite gneiss, banded gneiss, and migmatite (Fig. 1). The gneiss makes up the larger portion of the outcrop found in the area; it was found in almost all parts of the study area. The granite occurs at the northwestern and southeastern parts of the area.

The type of structures observed in the study area includes foliations, joints and veins, and solution cavities. The general trend of all the major joints and foliations as seen in the plotted rose diagram in the area mapped are concordant; they show a general orientation of NW-SE, while the vein is in the direction NE-SW (Fig. 2). This implies that the forces that caused the formation of the vein and foliation moved in the same direction while that of the joint is perpendicular to them.

Methodology

The cross-square array (direct current)

The square array (DC) resistivity technique is a modified resistivity method, wherein the magnitude and directions of the electrical anisotropy are determined (Leonard-Mayer 1984). An electrode array is rotated about its center so that the apparent resistivity is observed for several directions (Taylor and Fleming 1988; Habberjam 1979). The side length of the square is defined as spacing " a " and is equal to the depth of penetration. The array is expanded symmetrically about the center point with an increment in a spacing by $(2)^{1/2}$. The square array was used in this study because it requires 65 % less surface area than the Wenner or Schlumberger technique,

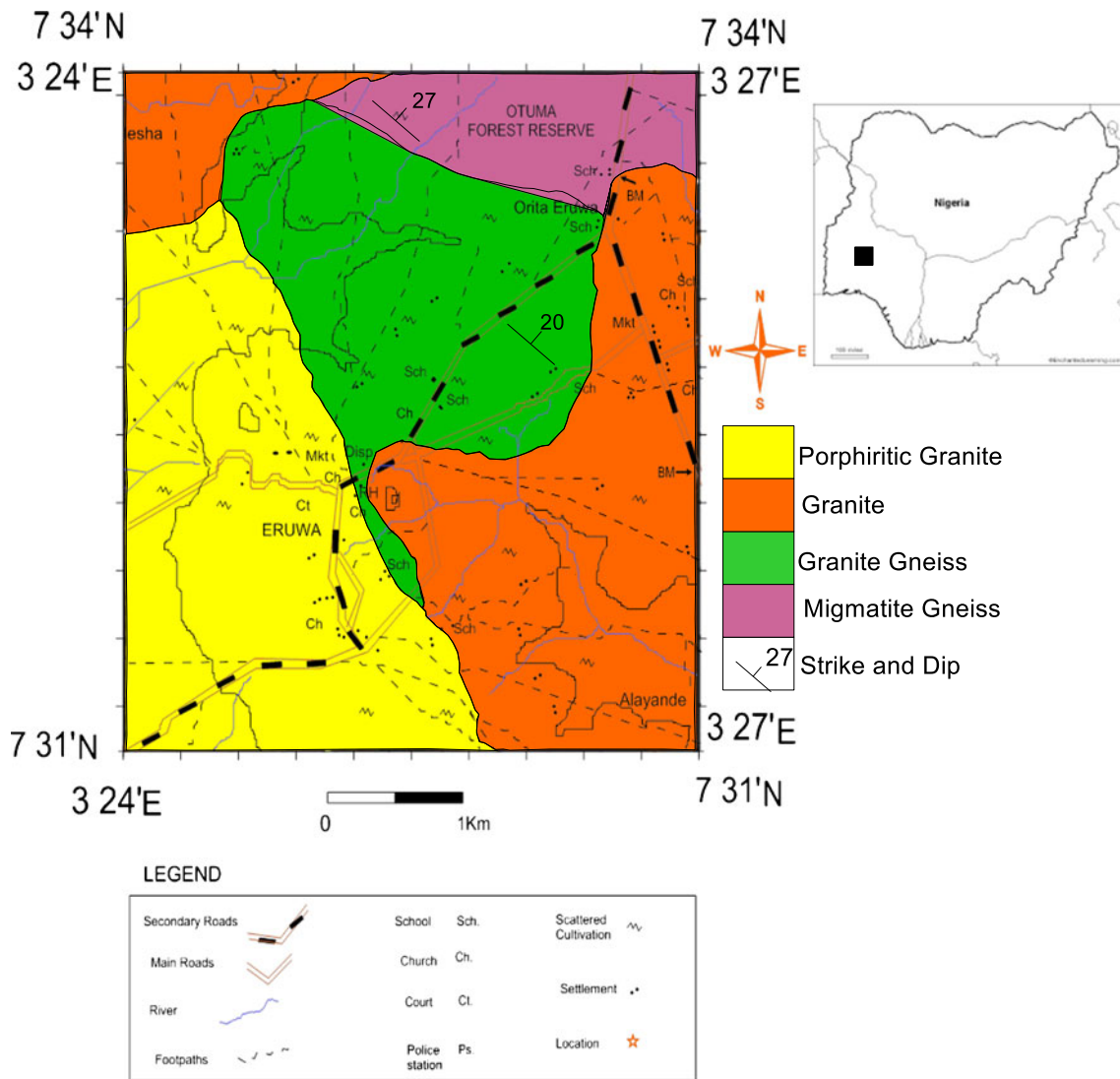


Fig. 1 Map showing the locations of the study area (*inset*: the location of the study area in Nigeria)

and it is more sensitive to anisotropy (Habberjam and Watkins 1967; Habberjam 1979). This technique is about twice as sensitive to anisotropy as linear array (Ehirim and Essien 2009). The starting orientation of square array is aligned in N-S direction. The apparent resistivity is measured from perpendicular sides, alpha (α) and beta (β) and diagonal gamma (γ) of each square (Fig. 3).

Apparent resistivity is determined from the equation

$$\rho_a = \frac{K \Delta V}{I}, \quad (1)$$

where ρ_a =apparent resistivity, K =geometric factor for the array, ΔV =potential differences in volts, and I =current magnitudes in amperes.

To determine the value for K ,

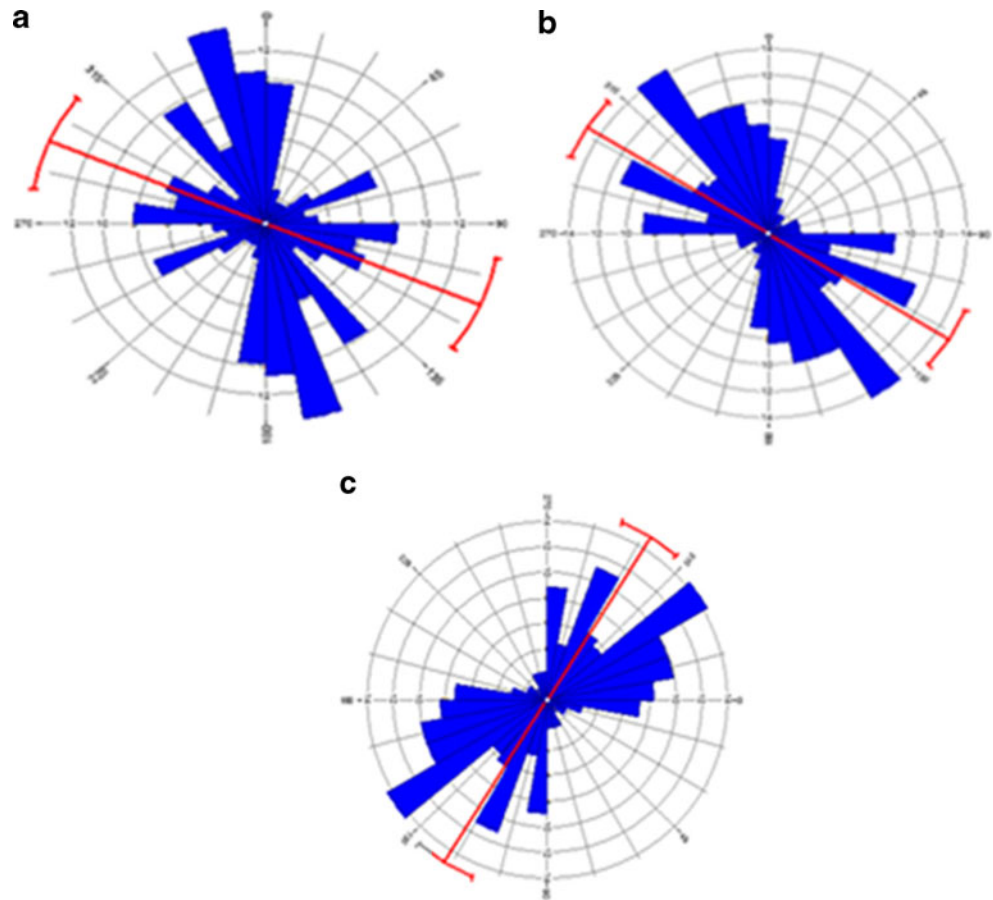
$$K = \frac{2\pi A}{2-(2)^{1/2}}. \quad (2)$$

Field operation

Resistivity soundings using CSA electrode configuration were carried out at ten locations within the study area (Fig. 4) with an Ohmega Terrameter to detect fractures, secondary porosity, fracture strike, azimuthal resistivity, and azimuthal inhomogeneity ratio in the crystalline bedrock of the selected locations within the study area. This array involves the rotation of the electrode array about its center so that apparent resistivity is observed for four different azimuths, namely, 0°, 45°, 90°, and 135°, along the surface at depths 10, 14, 20, 28, and 40 m.

The location of a measurement was assigned to the center point of the square with four people at the ends of the square expanding the electrodes symmetrically about the central point, in increment of $A(2)^{1/2}$ and one person at the central point taking measurement readings on the terrameter. The sounding was later recorded as a function of depth, and it was observed that measured apparent resistivity changed with

Fig. 2 Rosette diagrams showing the orientation of **a** foliation and **b** joints in NW-SE direction, while **c** veins are in NE-SW



the orientation of the array. In each of the ten study sites, the starting orientation of the square array is aligned in N-S direction, and three measurements were made, in which two are perpendicular measurements, namely, alpha (α) and beta (β), and one diagonal measurement gamma (γ). The α and β

measurements provided information on the directional variation of the subsurface apparent resistivity (ρ_a). The γ measurement served as check on the accuracy of the α and β measurements. The field arrangement of electrodes in the azimuthal resistivity survey is shown below (Fig. 5).

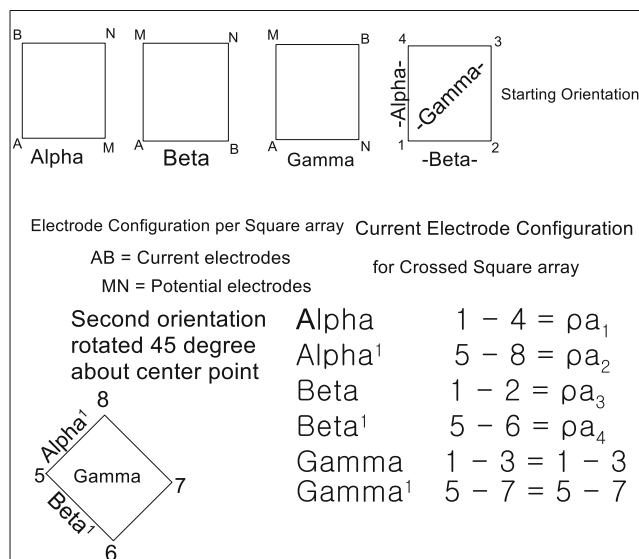


Fig. 3 Diagram showing the cross-square array arrangement (Lane et al. 1995)

Determination of fracture strike

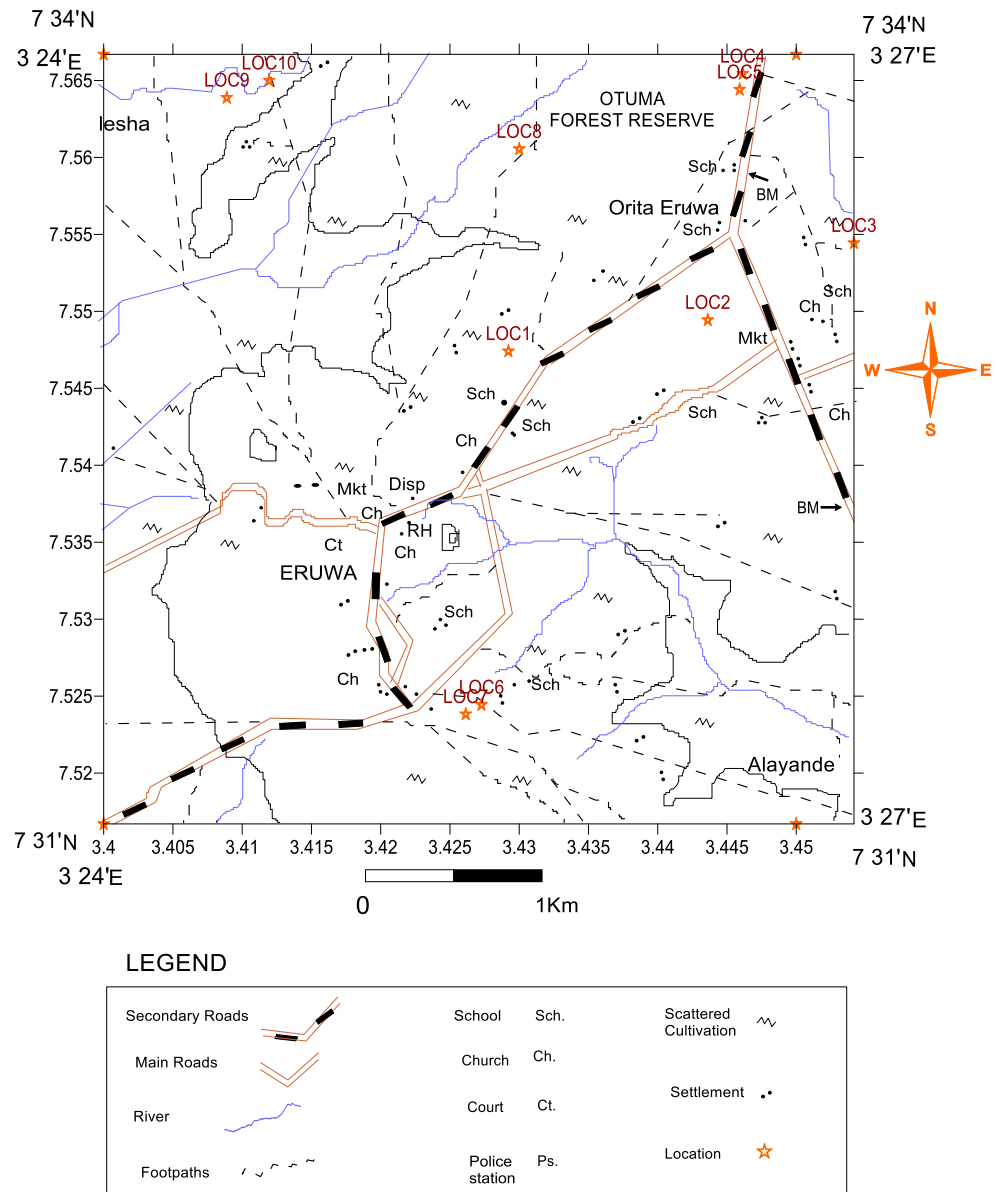
Cross-square array data were interpreted analytically in order to yield fracture strike. Habberjam (1975) calculated fracture strike using the formula below:

$$\theta = \frac{1}{2} \tan^{-1} \left(\frac{(D^2 - C^2)}{(A^2 - B^2)} \right), \quad (3)$$

where θ is the fracture strike, measured from ρ_{a1} ;

$$\begin{aligned} A &= \left\{ (\rho_{a3} + 3\rho_{a1})/2 + (\rho_{a4} + \rho_{a2})/(2)^{1/2} \right\} \left[2 + (2)^{1/2} \right] \\ B &= \left[(\rho_{a1} + 3\rho_{a3})/2 + (\rho_{a2} + \rho_{a4})/(2)^{1/2} \right] \left[2 + (2)^{1/2} \right] \\ C &= \left[(\rho_{a4} + 3\rho_{a2})/2 + (\rho_{a1} + \rho_{a3})/(2)^{1/2} \right] \left[2 + (2)^{1/2} \right] \\ D &= \left[(\rho_{a2} + 3\rho_{a4})/2 + (\rho_{a3} + \rho_{a1})/(2)^{1/2} \right] \left[2 + (2)^{1/2} \right] \end{aligned}$$

Fig. 4 Map showing the locations of cross-square array in the study area



ρ_{a1} , ρ_{a2} , ρ_{a3} , and ρ_{a4} are constituent resistivity measurements from the square array.



Fig. 5 Field arrangement of the cross-square array

Determination of secondary porosity

To calculate secondary porosity, it was first necessary to calculate the anisotropy (N) from the field data, using Habberjam's method (Habberjam 1975, 1979).

$$N = [(T + S)/(T - S)]^{1/2}, \quad (4)$$

where $T = A^{-2} + B^{-2} + C^{-2} + D^{-2}$;

$$S = 2[(A^{-2} - B^{-2})^2 + (D^{-2} - C^{-2})^2]^{1/2};$$

and A , B , C , and D are defined previously.

The secondary porosity is then estimated by

$$\varphi = \frac{3.41 \times 10^4 (N - 1)(N^2 - 1)}{N^2 C(\rho_{\max} - \rho_{\min})}, \quad (5)$$

Table 1 The resistivity values and mean geometric resistivity values of the square array in location 1

Location 1	0°			45°			90°			135°		
a (m)	ρ_α	ρ_β	ρ_m	ρ_a	ρ_β	ρ_m	ρ_a	ρ_β	ρ_m	ρ_a	ρ_β	ρ_m
10	129.3	149.9	139.2	197.1	202.6	199.9	183.9	226.7	204.2	198.2	186.2	192.1
14	260.7	157.9	202.9	251.4	259.0	255.1	213.1	297.3	251.7	242.2	222.2	231.9
20	330.7	249.2	287.3	319.8	306.5	313.1	380.9	398.6	389.7	317.4	293.4	305.2
28	585.7	652.9	618.4	420.1	469.1	443.9	889.1	594.7	727.2	530.4	367.8	441.7
40	678.7	1248.3	920.5	744.8	814.8	778.9	687.7	932.8	800.9	639.6	410.4	512.3

where ϕ =secondary porosity, $\rho_{\max}$ =maximum square array apparent resistivity, $\rho_{\min}$ =minimum square array apparent resistivity, and C =specific conductance of groundwater in microsiemens per centimeter.

Determination of azimuthal inhomogeneity ratio

This involves all the readings taken on the field, i.e., the alpha (α), beta (β), and gamma (γ) resistance values. The azimuthal

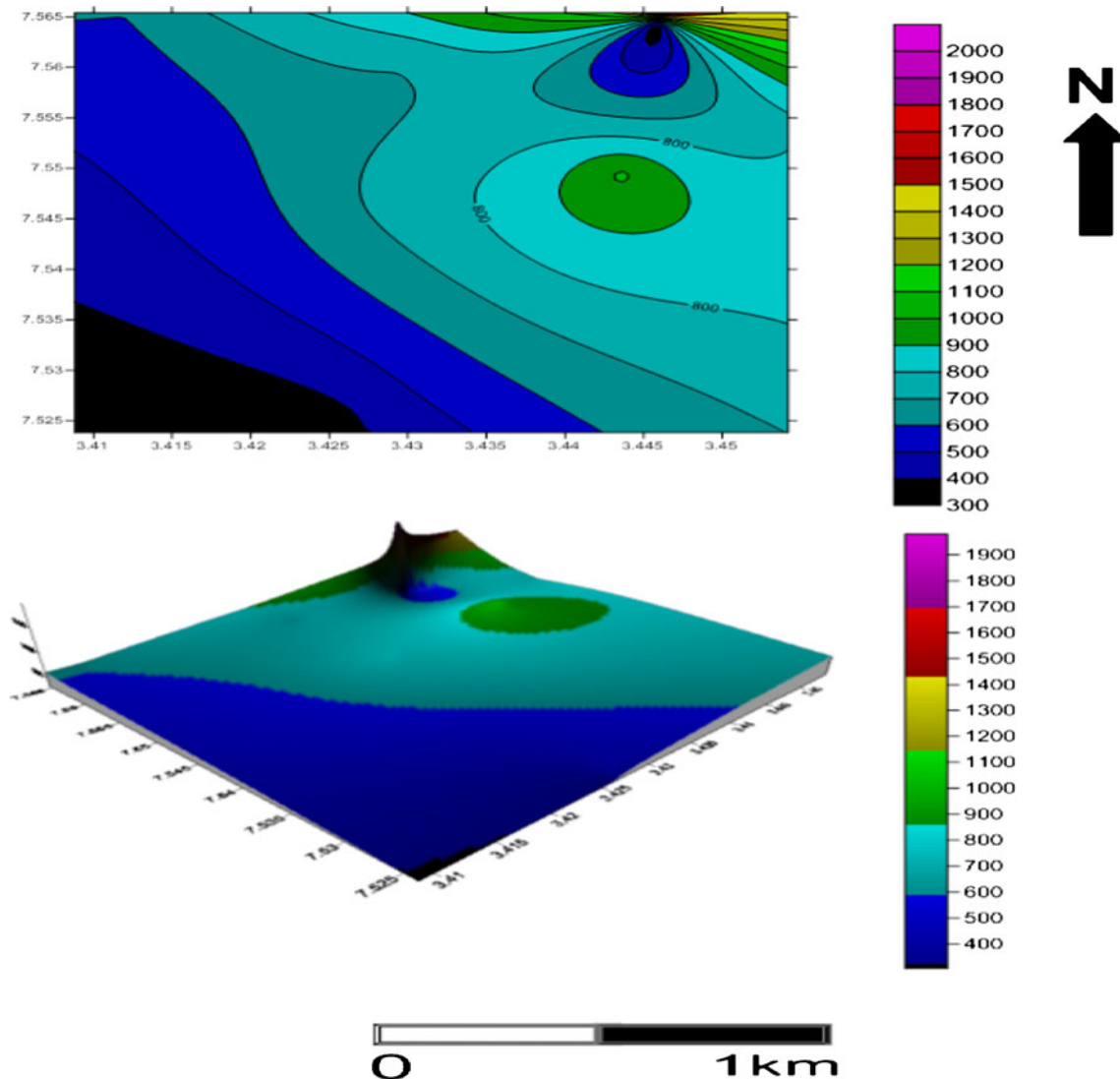
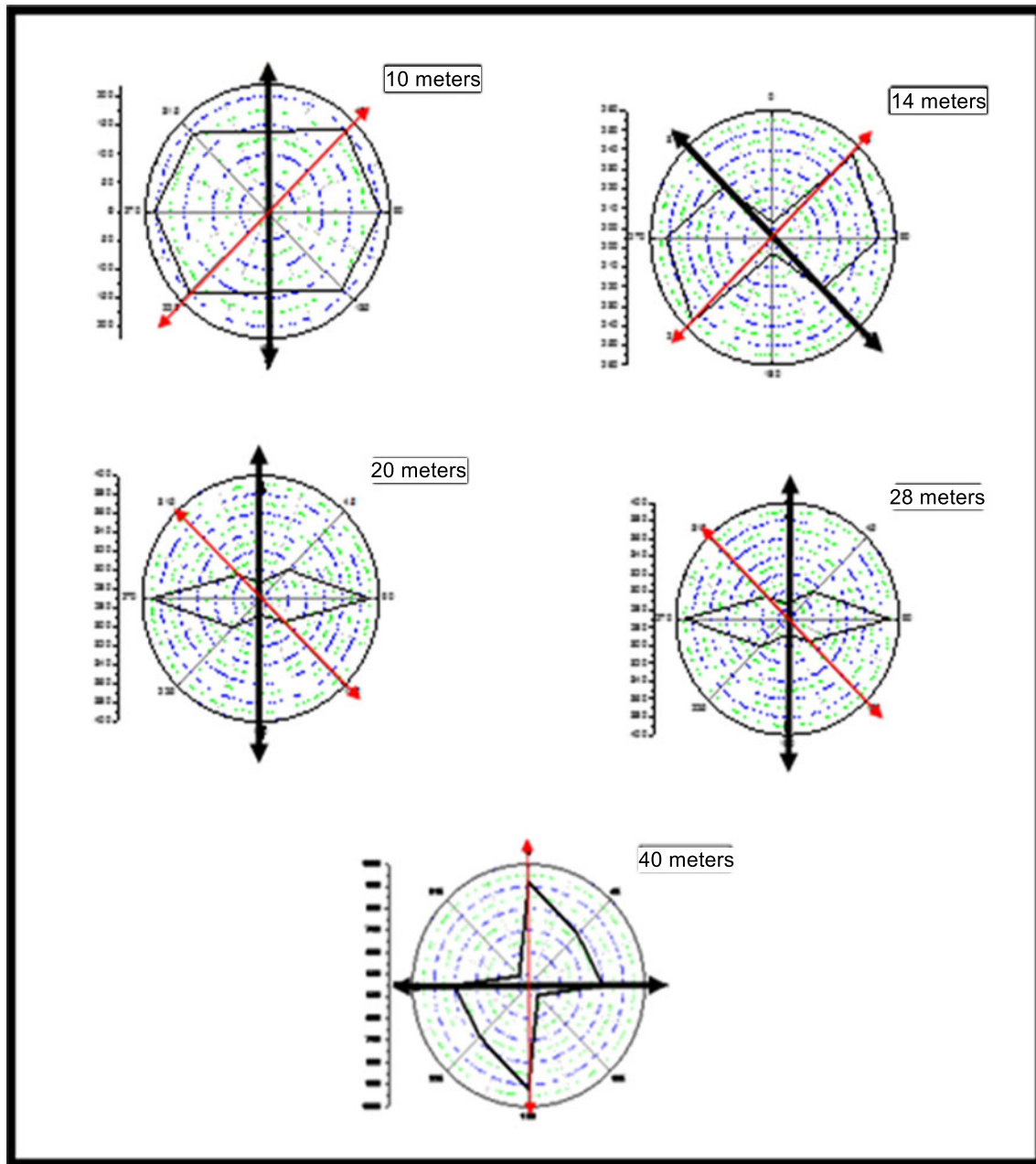


Fig. 6 Mean apparent resistivity map of the study area at 40 m

Table 2 The calculated fracture strike values for the locations in the study area

Spacing	Location 1	Location 2	Location 3	Location 4	Location 5	Location 6	Location 7	Location 8	Location 9	Location 10
10 m	1.005°	80.652°	150.823°	2.239°	127.356°	7.124°	13.708°	2.478°	11.728°	116.028°
14 m	142.633°	97.101°	24.127°	64.817°	133.407°	143.822°	24.149°	50.126°	128.419°	102.922°
20 m	5.286°	90.635°	16.973°	71.083°	150.248°	13.105°	17.260°	48.714°	93.942°	98.628°
28 m	12.601°	124.380°	150.224°	33.126°	160.313°	18.541°	60.882°	118.246°	86.497°	141.082°
40 m	87.653°	70.276°	9.828°	150.273°	27.508°	31.002°	39.610°	8.122°	4.096°	150.947°

**Fig. 7** The polar plot showing the fracture direction from the different electrode spacing for 10, 14, 20, 28, and 40 m in location 1. The *black and red arrows* show the direction of the primary and secondary fractures in the area, respectively

inhomogeneity ratio (AIR) is a measure of an apparent resistivity, and it is highly dependent on the orientation of electrodes (Habberjam 1972).

The azimuthal inhomogeneity is given as

$$\text{AIR}_{(x,y,r,\varphi)} = \frac{(\rho_a - \rho_b)}{\rho_m(x,y,r,\varphi)} = 2 \frac{\rho_a - \rho_b}{\rho_a + \rho_b} = 2 \frac{R_a - R_b}{R_a + R_b}, \quad (6)$$

$$\text{AIR} = 2R_\gamma / (R_\alpha + R_\beta). \quad (7)$$

Determination of azimuthal resistivity

Habberjam (1972) derived the expression for the variation of apparent resistivity with square array orientation over a homogenous anisotropic earth. For fractured rocks that approximate such a homogenous anisotropic earth medium, the predicted square array apparent resistivity in a given orientation is

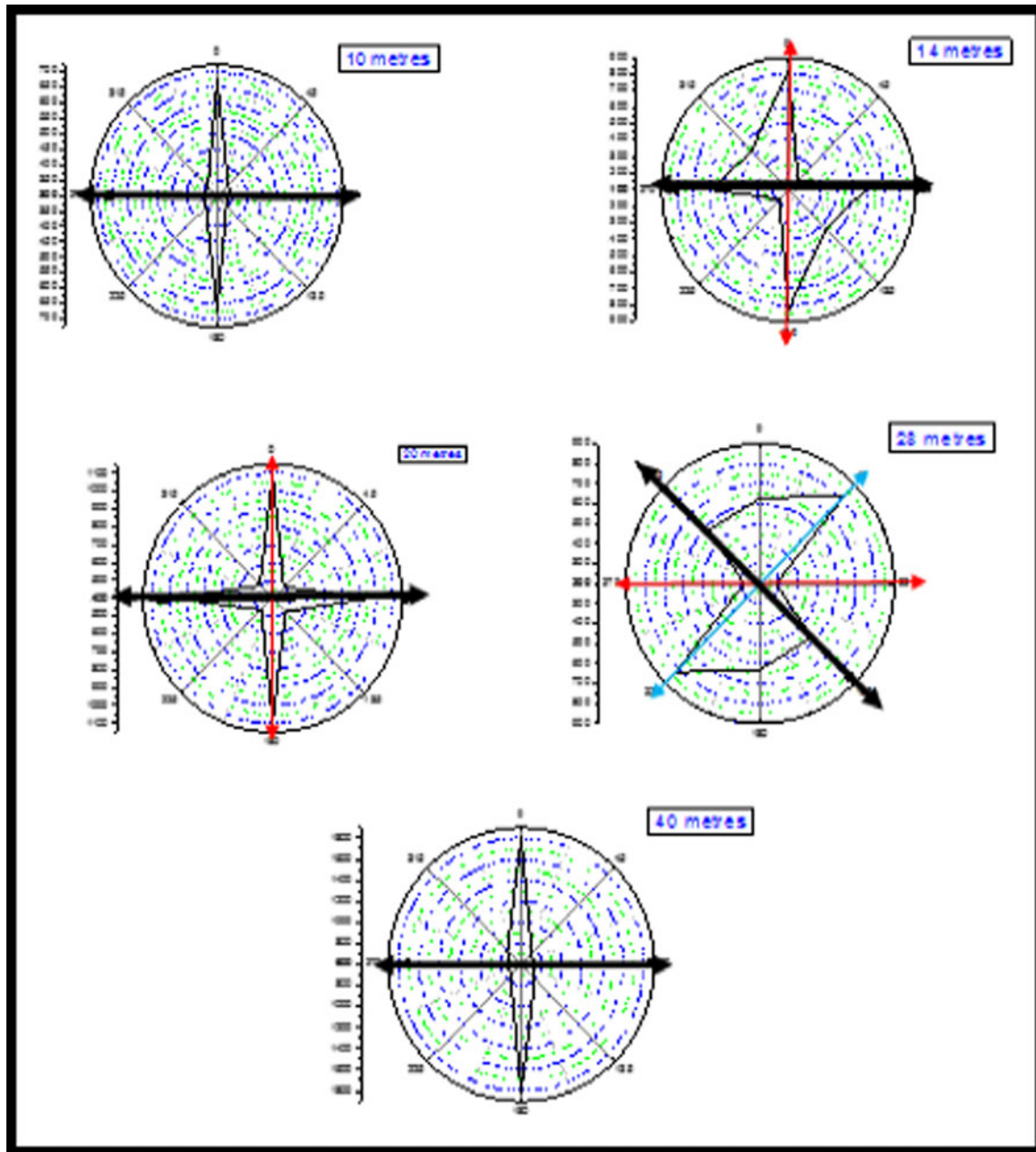


Fig. 8 The polar plot showing the fracture direction from the different electrode spacing for 10, 14, 20, 28, and 40 m in location 2. The black and red arrows show the direction of the primary and secondary fractures in the area, respectively

$$\rho_a = \frac{\rho_m}{2-(2)^{\frac{1}{2}}} \left(\frac{2}{[1 + (N^2-1)\cos\theta^2]^{\frac{1}{2}}} \right) - \left(\frac{1}{[2 + (N^2-1)(1 + \sin 2\theta)]^{\frac{1}{2}}} \right) - \frac{1}{[2 + N^2-1)(1-\sin 2\theta)]^{\frac{1}{2}}},$$

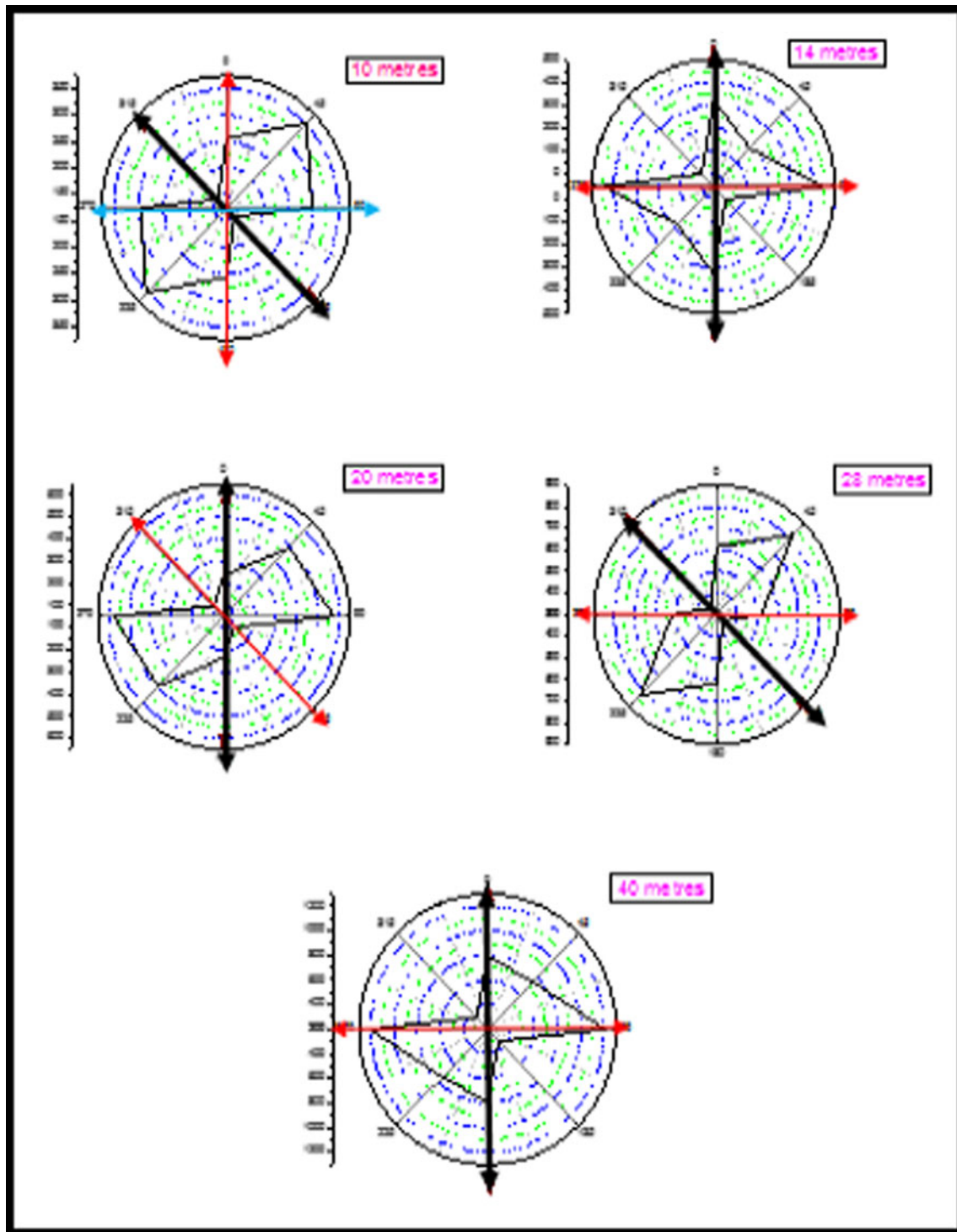


Fig. 9 The polar plot showing the fracture direction from the different electrode spacing for 10, 14, 20, 28, and 40 m in location 3. The *black, red, and blue arrows* show the direction of the primary, secondary, and tertiary fractures in the area, respectively

where $\rho_m = [(\rho_{at})(\rho_{ai})]^{1/2}$

ρ_{at} = apparent resistivity perpendicular to fractures

ρ_{ai} = apparent resistivity parallel to fractures

θ = angle measured from azimuth of current electrodes to fracture strike

N = effective vertical anisotropy = $[1 + (\lambda^2 - 1) \sin^2 \alpha]^{1/2}$

α = dip of fractures = $\pi/2$.

Determination of apparent anisotropy

For square array, the ratio of apparent resistivity measured perpendicular to fracture strike (ρ_{at}) to apparent resistivity parallel to fracture strike (ρ_{ai}) is called the apparent anisotropy (λ_a), and according to Darboux-Afouda and Louis (1989), it is given by the ratio

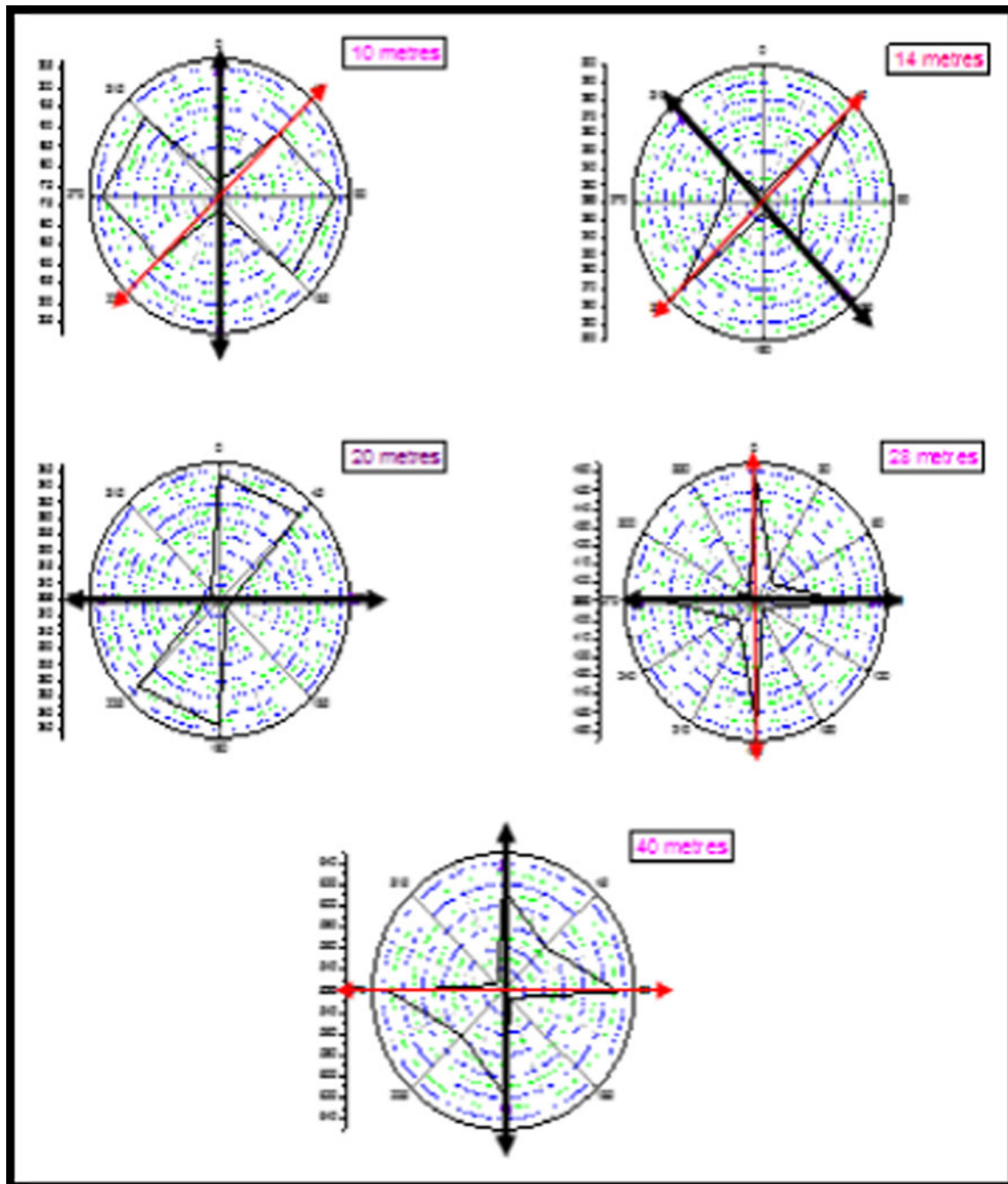


Fig. 10 The polar plot showing the fracture direction from the different electrode spacing for 10, 14, 20, 28, and 40 m in location 9. The black and red arrows show the direction of the primary and secondary fractures in the area, respectively

Table 3 The fracture strike direction from the polar plot in the study area; P= Primary; S= Secondary; T= Tertiary

A (m)	Location 1			Location 2			Location 3			Location 4			Location 5		
	P	S	T	P	S	T	P	S	T	P	S	T	P	S	T
10	N-S	NE-SW	–	E-W	–	–	NW-SE	N-S	E-W	N-S	NE-SW	–	NW-SE	NE-SW	–
14	NW-SE	NE-SW	–	E-W	N-S	–	N-S	E-W	–	E-W	NE-SW	N-S	NW-SE	NE-SW	–
20	N-S	NW-SE	–	E-W	N-S	–	N-S	NW-SE	–	E-W	N-S	–	NW-SE	NW-SE	–
28	N-S	NW-SE	–	NW-SE	E-W	NE-SW	NW-SE	E-W	–	NE-SW	NW-SE	–	NW-SE	N-S	–
40	E-W	N-S	–	E-W	–	–	N-S	E-W	–	NW-SE	NE-SW	–	N-S	NE-SW	–
A (m)	Location 6			Location 7			Location 8			Location 9			Location 10		
	P	S	T	P	S	T	P	S	T	P	S	T	P	S	T
10	N-S	NE-SW	E-W	N-S	NE-SW	–	N-S	NE-SW	–	N-S	NE-SW	–	E-W	N-S	–
14	NW-SE	E-W	–	N-S	–	–	NE-SW	E-W	N-S	NW-SE	NE-SW	–	N-S	E-W	–
20	E-W	NW-SE	NE-SW	N-S	–	–	NE-SW	NW-SE	–	E-W	–	–	E-W	–	–
28	N-S	NE-SW	E-W	NE-SW	–	–	N-S	N-S	–	E-W	N-S	–	NW-SE	NE-SW	–
40	N-S	NE-SW	–	NE-SW	E-W	–	N-S	E-W	–	N-S	E-W	–	NW-SE	–	–

$$\lambda_a = \frac{N \left[(N^2 + 1)^{1/2} - 1 \right]}{\left[(N^2 + 1)^{1/2} - N \right]}.$$

Results and interpretation

Mean geometric resistivity

In the cross-square array resistivity measurements, the α and β readings were converted to single measurements by calculating their mean values ρ_m . These mean resistivity values represent the average values for the four azimuths in all the locations in the area; the mean resistivity values for location 1 are presented in Table 1. The results of apparent resistivity obtained at different azimuths and depths as seen in Table 1 below were found to vary with orientation of the array at each depth. Generally, for all the locations, the resistivity value increases with depth; i.e., the lowest mean resistivity value (ρ_m) was mostly seen at depth 10 m while the highest value was mostly seen at depth 40 m (Table 1). At 40 m, no resistivity higher than that of the previous depth is noticed on the map, while

low resistivity is noticed in southwest direction of the map (Fig. 6).

Fracture strike and anisotropy polygons

The fracture strike was determined analytically and graphically using Habberjam (1975). The calculated values of fracture strike are presented in Table 2. To further aid the interpretation of fracture strike, the cross-square array data were further analyzed by plotting the apparent resistivity against azimuths at spacing ranging from 10 to 40 m on azimuthal polar diagram (Figs. 7, 8, 9, and 10). The longest axis of the ellipse in the polar plot indicates maximum resistivity of the rock mass; the principal fracture strike is perpendicular to the direction of maximum resistivity. The fracture strikes at different electrode spacing are represented with colored arrows pointed at both ends. In respect to the azimuthal polar plots, the orientation of the fractures and other geometrical features are identified as a function of depth ranging between 10 and 40 m.

The polygons identified primary, secondary, and tertiary fracture strikes. The primary fracture strikes are represented with a black arrow, secondary fracture strikes are represented

Table 4 The calculated fracture strike values

Spacing	Location 1	Location 2	Location 3	Location 4	Location 5	Location 6	Location 7	Location 8	Location 9	Location 10
10 m	1.005°	80.652°	150.823°	2.239°	127.356°	7.124°	13.708°	2.478°	11.728°	116.028°
14 m	142.633°	97.101°	24.127°	64.817°	133.407°	143.822°	24.149°	50.126°	128.419°	102.922°
20 m	5.286°	90.635°	16.973°	71.083°	150.248°	13.105°	17.260°	48.714°	93.942°	98.628°
28 m	12.601°	124.380°	150.224°	33.126°	160.313°	18.541°	60.882°	118.246°	86.497°	141.082°
40 m	87.653°	70.276°	9.828°	150.273°	27.508°	31.002°	39.610°	8.122°	4.096°	150.947°

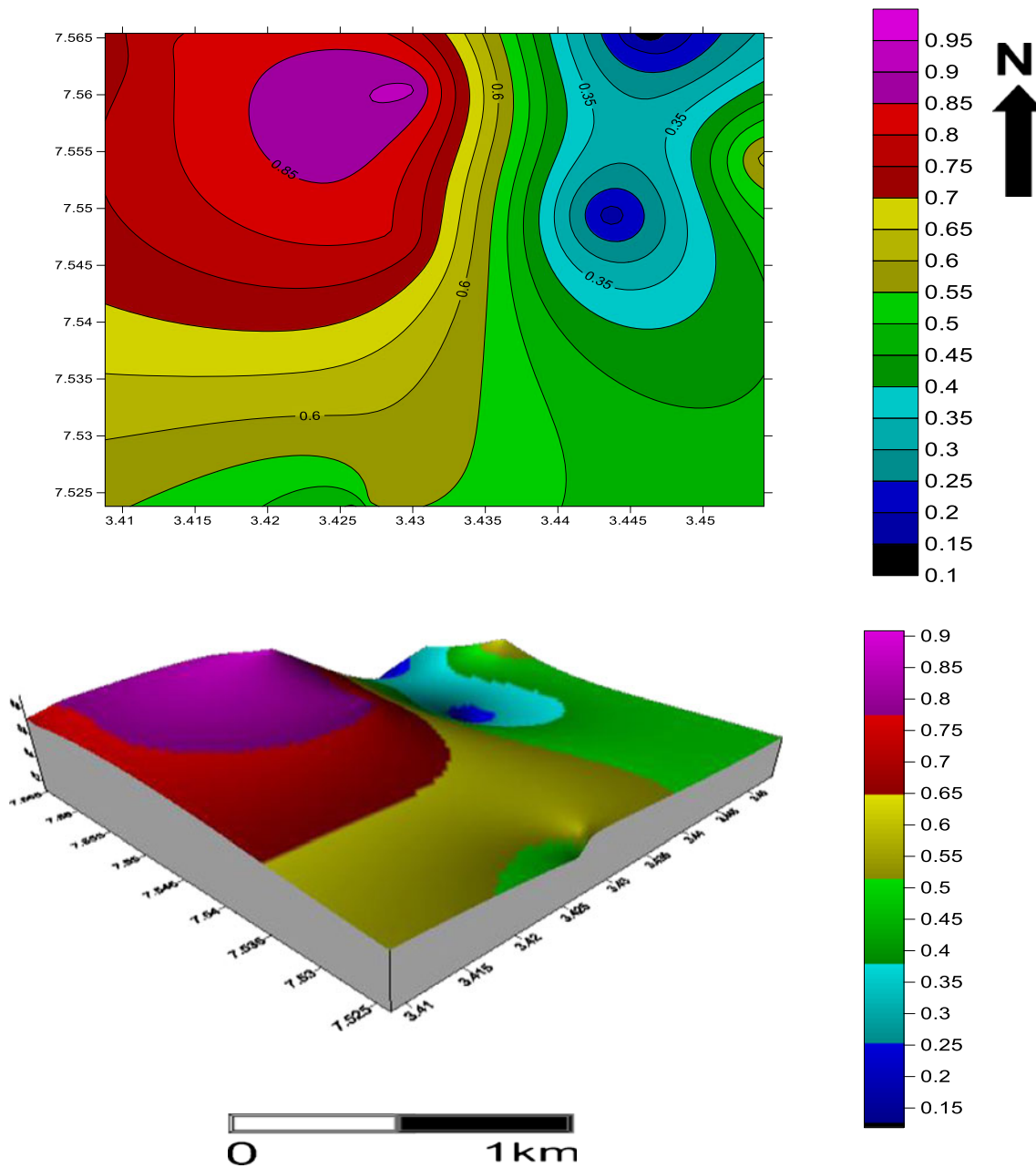


Fig. 11 Secondary porosity map for the study area at 40 m

with red pointed arrows, while the tertiary fracture strikes are represented with a blue pointed arrow. The electrical

anisotropy in the study area trends in N-S, NW-SE, NE-SW, and E-W directions. These multiple structural trends observed

Table 5 Values for azimuthal inhomogeneity ratio (AIR) in the study area

Spacing (m)	Location 1				Location 2			
	0°	45°	90°	135°	0°	45°	90°	135°
10	-0.99693	0.070336	0.21955	-0.01926	0.611553	0.151676	0.103593	-0.58391
14	-0.29576	0.14189	0.481601	-0.06088	0.190856	0.242266	0.136786	-0.46453
20	-0.23743	0.287868	0.347467	-0.0677	0.178514	-0.19573	0.024404	-0.60008
28	-0.16157	0.293342	0.312272	-0.07441	-0.1787	0.240542	-0.60296	-0.47561
40	0.545333	0.358382	0.496954	-0.22527	0.184931	0.240097	0.11415	-0.34756

Table 6 Secondary porosity values for locations 1–10

Spacing	Location 1	Location 2	Location 3	Location 4	Location 5	Location 6	Location 7	Location 8	Location 9	Location 10
10	0.97	0.22	0.34	0.12	0.08	0.27	0.72	0.99	0.3	0.65
14	0.54	0.13	0.3	0.38	0.1	0.41	0.9	0.84	0.27	0.77
20	0.82	0.19	0.5	0.7	0.09	0.23	0.53	0.78	0.44	0.82
28	0.43	0.23	0.07	0.15	0.13	0.64	0.59	0.83	0.52	0.8
40	0.79	0.17	0.62	0.11	0.18	0.58	0.44	0.91	0.71	0.79

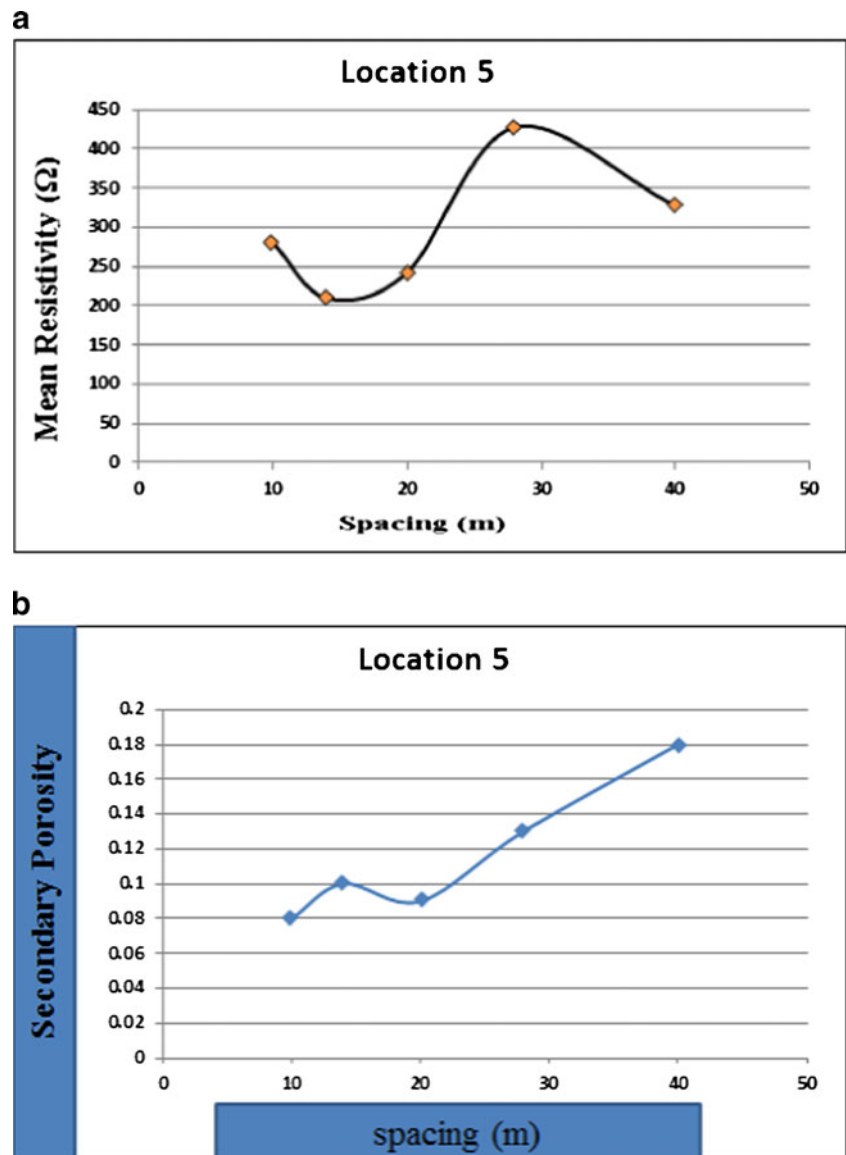
in the anisotropy figures may be a result of intersection of joints.

Table 3 shows that the fracture directions result from the polar plots shown for all the locations. The primary fractures in location 3 are oriented along N-S and NW-SE directions, while secondary fracture lies mainly along N-S, E-W, and

NW-SE, and tertiary fractures are in E-W direction. Other locations can be seen in this table.

The results of the analytical and graphical fracture strikes show that fracture in the study area lie predominantly at N-S, NW-SE, and E-W while NE-SW is less prominent. From Tables 3 and 4, it was observed that the calculated fracture

Fig. 12 The plots of **a** mean resistivity and **b** secondary porosity for location 5



strike values correspond with the result from the polar plot, i.e., the fracture direction of the study area.

High-fracture porosity is prominent at 40 m in the study area, and it is noticed in the whole of northwest, southwest, and southeast directions, while low-fracture porosity only trend in northeast direction of the map (Fig. 11).

AIR

The AIR is a measure of an apparent resistivity, and it is highly dependent on the orientation of electrodes (Habberjam 1972). The value range showed the degree of anisotropy in the study area. The AIR values obtained from the square array measurements in the study area are shown in Table 5. From this table, values in location 1 ranges from -0.23 to 0.5 ; the lowest and highest values are both seen at 0° , for 10 and 40 m, respectively. In location 2, value ranges from -0.60 to 0.61 . The lowest and highest values are seen at 90° for 28 m and 0° for 10 m, respectively.

Discussion

When the polar diagram conforms to an ellipse, it is taken to represent anisotropy homogeneity (Busby 2000; Senos Matias 2002). The circular pattern of the plot exhibits rock mass without fault/fracture orientation which means the rock is isotropic. The elliptic shape of the polar diagrams in the area therefore indicates an anisotropy condition. According to Habberjam and Watkins (1967), the observed changes in apparent resistivity (ρ_a) with azimuth can be interpreted as an indicator of fracture anisotropy and the presence of aligned

vertical or sub-vertical fractures causes a fractured rock mass to exhibit azimuthal anisotropic behavior.

Mean apparent resistivity vs secondary porosity

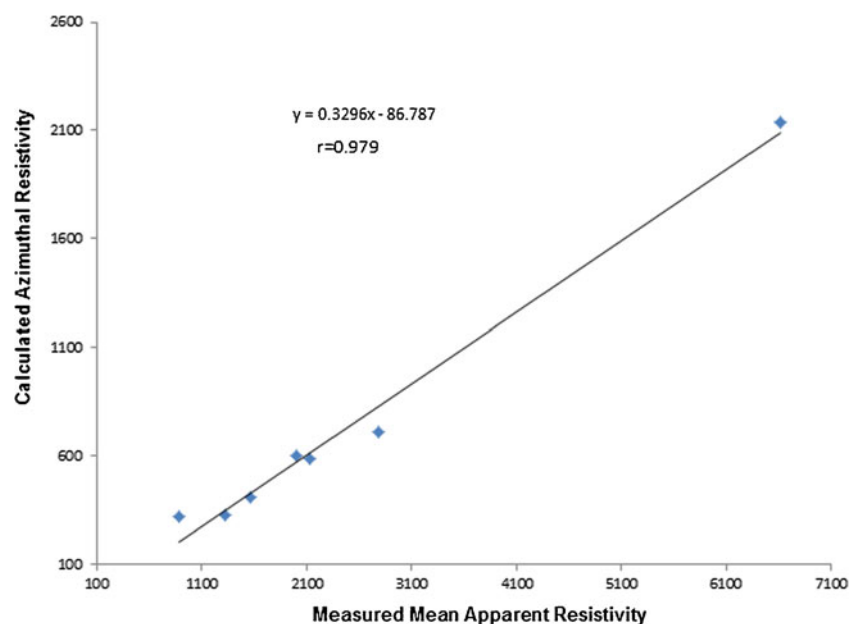
The mean resistivity values for locations 1–10 range from 114.8 to 2136.5 Ωm (Table 4), and secondary porosity (fracture porosity) estimate from spacing 10–40-m data ranges from 0.07 to 0.99 (Table 6).

According to George et al. (2010), a comparison was made for the mean apparent resistivity and the calculated secondary porosity. A decreased mean resistivity and an increased secondary porosity at a point are interpreted as fractures zones. The plots in Figs. 7, 8, 9, and 10 show that area of decreased mean apparent resistivity and increased calculated secondary porosity are located at 10, 28, and 40 m. From the graphs below (Fig. 12a, b), the fracture zone is probably located at 10 and 40 m for location 5.

Correlation between measured mean apparent resistivity and calculated azimuthal resistivity

The measured mean apparent resistivity and the calculated azimuthal resistivity results were correlated for electrode spacing of 40 m, and this covers all the locations in the study area. From the graphs below, it was evident that the two resistivity values (measured mean resistivity and calculated apparent resistivity) correlate with one another. The correlation percentage is 0.97; this is more than 0.5, which is the average percentage of correlation. This shows that the two resistivity values (measured mean apparent resistivity and the calculated azimuthal resistivity) are strongly correlated (Fig. 13).

Fig. 13 Graph showing correlation between calculated azimuthal resistivity and measured mean apparent resistivity at distance spacing of 40 m ($r=0.979$)



Summary and conclusion

The results from field measurements showed that apparent resistivities obtained at different azimuth and depth (spacing) were found to vary with orientation of the array at each depth. The observed changes in apparent resistivity (ρ_a) with azimuth is an indicator of fracture anisotropy, and the presence of aligned vertical or sub-vertical fractures causes a fractured rock mass to exhibit azimuthal anisotropic behavior. Generally, for all the locations, the resistivity value increases with depth; i.e., the lowest mean resistivity values (ρ_m) were mostly seen at depth 10 m while the highest values were mostly seen at depth 40 m (Table 1).

Results from polar plots showed that fracture directions change with depth. The interpreted polar plots indicate multiple fracture directions in the area. Primary fractures in the area lie predominantly at N-S, NW-SE, and E-W; secondary fractures lie predominantly at NE-SW and E-W; and the few tertiary fractures shown lie predominantly at E-W. These multiple structural (N-S (15°), NW-SE (145°), and E-W (90°)) trend observed in the anisotropy figures may be a result of intersection of joints present in the study area. The calculated fracture strike results from polar plot correspond with each other. Comparison of mean apparent resistivity and secondary porosity plots revealed that there are four major fracture zones in the study area, and this is due to a decreased mean apparent resistivity and an increased secondary porosity at the same points on the graph for the four locations, while the remaining locations have different points of decreased mean apparent resistivity and increased porosity. This results further show that most fractures in the study areas have rock mass being less intensely fractured and less permeable. The calculated azimuthal resistivity shows that values increase with electrode spacing, indicating that fracture is one of the causes of anisotropy in the area. Correlation between the measured mean apparent resistivity and the calculated azimuthal resistivity shows a strong correlation confirming a certainty of accurate data measurement and anisotropy in the study area.

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