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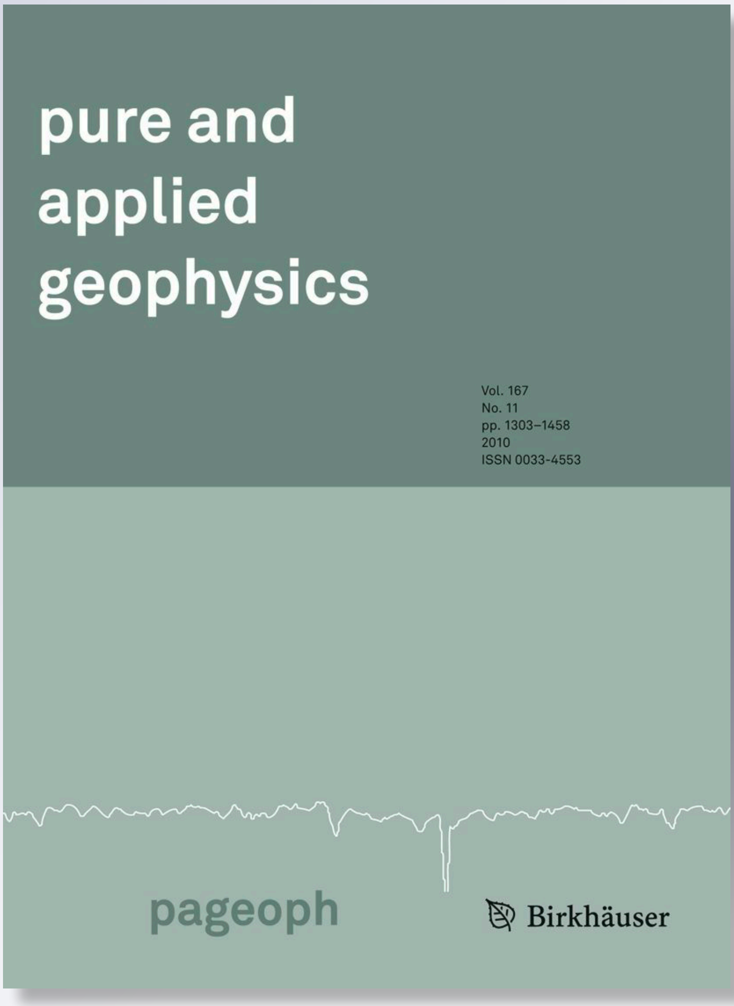

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Pure and Applied Geophysics

Determining Subsurface Fracture Characteristics from the Azimuthal Square Array Resistivity Survey at Igarra, Nigeria

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Abstract—Fractures are deformations in rocks with discontinuity. They are important in a number of ways. Their presence significantly influences the strength and engineering properties as well as the hydraulic characteristics of rocks. Fractures may extend to the surface where they are observed and studied at outcrops. On the other hand, they may terminate in the subsurface or may be covered by overburden which makes them impossible to be studied and characterized at the ground surface. There has been an increasing interest in the location and characterization of fractures by earth scientists, engineers and other scientists, both at the surface and the subsurface. However, the unavailability or inaccessibility of good outcrops makes it imperative to develop methods and tools for studying fractures in the subsurface. Geophysical methods such as the resistivity methods have been very useful in this regard. The Azimuthal Square Array Resistivity Survey was used in this project to locate and characterize subsurface fractures in the crystalline rocks at Igarra. Results from the analysis and interpretation of the field data showed that the dominant fracture strike orientation is in the NNW–SSE direction. This compares well with the results of surface geologic mapping data which gave the general fracture strike orientation as N–S; however, the major large and extensive fractures are striking NNW–SSE. This information is very useful in modeling groundwater flow and contaminant transport; planning proper waste management programs as well as the Environmental Impact Assessment analysis for the study area. This study once more illustrates the satisfactory use of non-invasive geophysical methods in characterizing fractures in the subsurface especially where quality outcrops are not available or inaccessible.

1. *Introduction*

Fractures are important in a number of ways. Their presence significantly affects the strength and engineering properties of rock; hence, they must be carefully studied in civil engineering operations such as those involved in the construction of tunnels, bridges, dams and buildings. Fractures are also sites of mineralization, since dilatational fractures developed under extension are usually filled in by vein materials deposited from aqueous solutions in the space created as the fractures open. Such veins are valuable sources of ores. The presence of fractures in rocks (especially crystalline rocks) can potentially increase the hydraulic properties (porosity and permeability) of the rock by several orders of magnitude. Thus, the availability and vulnerability to contamination of groundwater can be reasonably assessed if valuable information on fracture characteristics are provided. This information is very useful for modeling groundwater flow and contaminant transport since flow paths are expected to be preferentially along the dominant fracture strike direction. Inputs from such models are useful in analyzing the Environmental Impact Assessment (EIA) of the area of investigation.

There has been an increasing interest in the location and characterization of fractures by Earth scientists, engineers and other scientists, both at micro and macro scales; and at the Earth's surface and subsurface. When fractures extend to the surface, they are relatively easy to locate and characterize by surface geologic mapping and modeling. However, unavailability or inaccessibility of outcrops makes it imperative to develop methods and tools for locating and characterizing fractures in the subsurface. This is also important as fracture parameters, such as fracture trend or orientation, fracture density, length and aperture, as well as fill, vary with depth and location. Geophysical methods such as the resistivity methods are very useful in this regard. Several innovations and landmark research findings have been made in pursuit

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of this goal amongst which is the Azimuthal Square Array Resistivity Survey method.

All resistivity methods employ an artificial source of current (DC or low frequency AC), which is introduced into the ground through a point metallic stake (electrode) or long line contact. The purpose of electrical resistivity surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. Resistivity is a measure of a materials resistance to the flow of electrical current.

The Azimuthal Square Array Resistivity Survey is done by rotating the whole electrode array through 180° at regular increments. The square array was designed by Habberjam (1967) to solve the problem of poor sensitivity and orientation dependent resistivity values obtained using a collinear array. In addition, square array data are useful in quantifying the degree of subsurface inhomogeneity and requires about 65% less surface area (Lane *et al.*, 1995) compared to the collinear arrays. By using a square array, measurements are less dependent on array orientation, yet sensitive to the position of the array center.

The square array employs the use of four electrodes—two current and two potential electrodes—arranged at the corners of a square of size ‘a’. Measurements are recorded at the center of the array. To estimate the variation of apparent resistivity with depth, the array is symmetrically expanded about its center in simple multiples (Fig. 1), while to obtain apparent resistivity measurements along different azimuths, complete array expansions are rotated at angular increments through 180°. The orientation of the azimuth of measurement is the line between the two current electrodes. Using the Azimuthal Square Array Resistivity Survey method, the azimuth of existing fracture zones is generally indicated by a decrease in resistivity along a particular azimuth relative to the others. Hence, plots of apparent resistivity values as a function of azimuth are used to characterize electrical anisotropy. Circular plots are characteristically interpreted to indicate electrical isotropy, signifying the absence of measurable fracture set of preferred orientation, or small volume of rock investigated (Busby and Peart, 1997). On the other hand, elliptical plots are generally construed to signify anisotropic response within the rock mass.

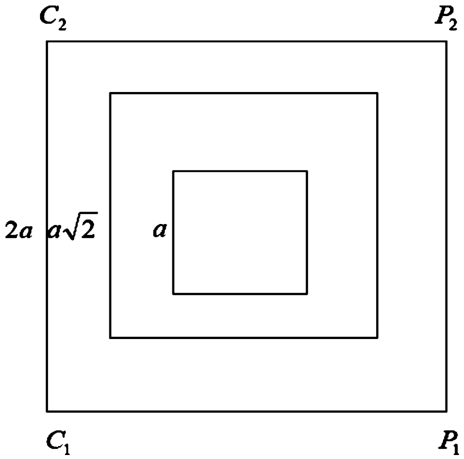

Figure 1
Symmetrical expansion of the *square array* about its centre (Habberjam and Watkins, 1967)

2. *Regional Geology and Tectonics of Igarra*

Igarra is part of the southwest block of the Nigerian Basement Complex. The Nigerian Basement Complex lies slightly to the east of the West African Craton in the terrain generally described as the Pan-African belt. It is bounded to the west by the Buen-Togo series and to the east by the Cameroon Mountains. Lithologically, Igarra comprises mainly the slightly migmatised to unmigmatised schist belt (Igarra schist belt) (Fig. 2) bounded and underlain by the Migmatised–Gneiss Complex and intruded by the Pan-African Older Granites which form good topographic features rising up to over 100 m above the surrounding terrains. The contact between the migmatite–quartize complex and the schist belt are sometimes fault bounded. The Igarra schist belt runs for about 60 km in a generally NNW–SSE direction (Rahaman, 1976) and comprises quartz-biotite schist, mica schist, quartzite and quartz schist, calc-silicate and marble, and metaconglomerate.

The quartz-biotite schist is the dominant rock type in the area. The rock is dark coloured with narrow alternating dark and light grey bands. The darker bands contain more biotite than the lighter bands which are relatively richer in quartzose material. Either of the bands can increase in thickness at the expense of the other such that the rock

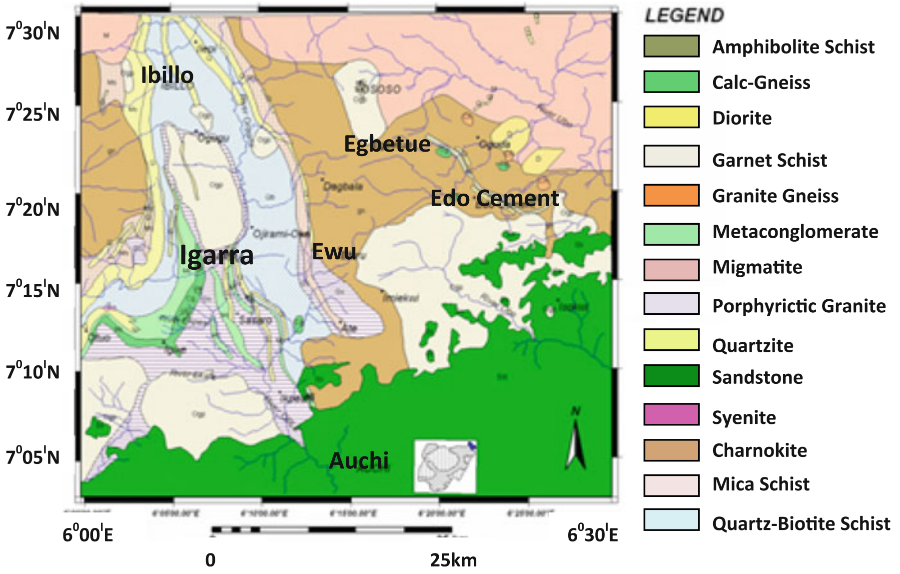

Figure 2
Geologic map of the Igarra area showing lithology (Anifowose *et al.*, 2006)

can locally assume gneissic or schistose texture. The unit has been migmatised and granitised in some places as a result of emplacement of the Pan-African granites.

The schist belt, which is of the upper greenschist facies, is believed to be a relic of a supercrustal cover which was infolded into the Migmatised–Gneiss Complex (McCurry, 1973). Several workers have proposed models for the tectonic evolution of the schist belt in relation to the basement complex. Ajibade (1980) suggested an initial crustal extension and continental rifting at the West African craton margin about 1,000 Ma leading to the formation of graben-like structures in western Nigerian and the subsequent deposition of the rocks of the schist belts. Closure of the ocean at the cratonic margin about 600 Ma and crustal thickening in the Dahomeyan led to the deformation of the sediment, the reactivation of pre-existing rocks and the emplacement of the Pan-African granites. Recognition of sutures along the eastern margin of the West African craton led Turner (1983) to relate the schist belt to the subduction processes in the cratonic margin. He is of the view that the schist belt was deposited in a back-arc basin developed after the onset of subduction at the cratonic margin. However, the distance of the nearest Nigerian schist belt from the site of subduction is at least 200–250 km exceeding the 100–150 km from arc to back-arc basins in present day arc system (Gass, 1981). The possibility that the schist belt may represent additional micro-continent separating pre-existing macro-continents has also been suggested by McCurry and Wright (1977).

3. *Methodology*

Surface geological field mapping was first carried out to study the rocks and structural features in the study area. In the process outcrops were identified and studied in detail. Measurements taken include trend/orientation of fractures, fold and fold axis orientation, lineation and fracture attitude and length. This was followed by the Azimuthal Square Array Resistivity Survey to map the dominant orientation of subsurface fracture strike. Three sites with minimal topographic undulations were chosen for this during the surface geological mapping. This is important because topographic variations causes artificial terrain induced conductive and resistive anomalies in

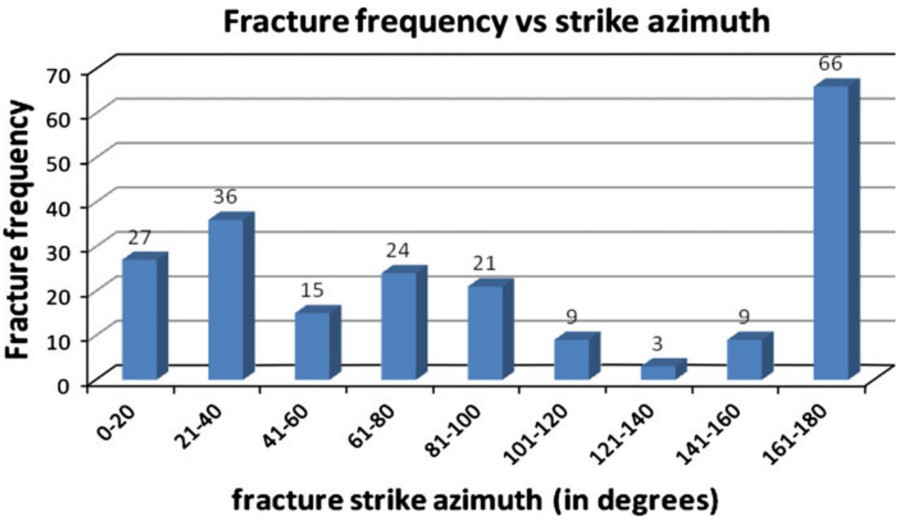

Figure 3
Plot of fracture frequency against fracture strike azimuth

the field (Telford *et al.*, 1990). Four potential and current electrodes were arranged at the sides of a square about the same center point. This center point is the measurement location. The desired depth of current penetration and investigation governed the choice of minimum and maximum electrode spacing. Edwards (1977) estimated the square array investigative depth to be 0.451 times the electrode spacing/sides of the square (a). The minimum and maximum electrode spacing was 5 and 40 m respectively giving depth of investigation ranging from 2.3 to 18 m. The minimum spacing value was progressively increased by the factor $a\sqrt{2}$ (Fig. 1). To measure the directional variation of resistivity with the azimuth, initial array orientation was aligned in the direction of true north. Measurements along other azimuths were taken by progressively rotating the square array about its center at angular increment of 22.5° through 157.5°. This is done for all electrode spacing and at all survey sites.

Expected sources of noise include resistivity variations near the current and potential electrodes, and leakage of current due to poor electrode–ground contact. Current leakage due to poor electrode contact was minimized by ensuring good electrode–ground contact. Correct electrode positioning and instrument calibration was confirmed before measurements were taken while personal errors were avoided during sounding.

4. Data Analysis and Results

The attitude of fractures mapped on outcrops was grouped according to their strike azimuth in intervals of 20°. These were subsequently plotted for easy appreciation of the dominant orientation of the strike of the fractures in the study area as observed from surface geologic mapping (Fig. 3). The plot of the surface geological mapping data showed that the dominant fracture strike direction is in the N–S direction.

Apparent resistivity values were computed from the Azimuthal Square Array Resistivity Survey data using the following relations:

$$\ell_{\mathrm{a}} = \frac{K\Delta V}{I} \tag{1}$$

where ℓ_{a} is the apparent resistivity in Ωm, k is the geometric factor, ΔV is the measured potential difference in volts, I is the applied current in amperes.

For the square array, the geometric factor is given by:

$$K = \frac{2\pi a}{2 - \sqrt{2}} \tag{2}$$

(Habberjam and Watkins, 1967).

where a = the square array side length in meters.

The computed apparent resistivity values are presented in Tables 1, 2, 3. These values were

Table 1

Azimuthal resistivity values measured at Anglican Science College (ASC), Igarra survey site

a (m)	K	0°	22.5°	45.0°	67.5°	90.0°	112.5°	135.0°	157.5°
5	53.6	160.8	181.1	171.5	189.5	198.7	159.3	146.7	170.8
7.1	75.8	112.5	127.1	137.1	151.4	158.1	130.5	110.1	111
10	107.3	81.8	126.5	122.1	146.9	137	102.7	97.6	91.2
14.1	151.2	80.1	90.4	124.6	146.2	139.8	76.3	94.3	92.1
20	214.5	84.5	133.1	149.1	169.4	137.4	104.6	116.5	109.6
28.3	303.5	85	135	186.8	220.1	203.7	149.1	113.9	101.7
40	429	146.1	174.1	206.4	253.4	231.6	162.2	183.3	149.6

Resistivity values are in Ωm

Table 2

Azimuthal resistivity values measured at Technical and Science College (TSC), Igarra survey site

a (m)	K	0°	22.5°	45.0°	67.5°	90.0°	112.5°	135.0°	157.5°
5	53.6	161.7	236.9	286.6	352.4	298.2	264.2	237.3	292.9
7.1	75.8	76.6	156.4	185.7	208.9	185.1	142.9	125.9	120.3
10	107.3	41.3	103.2	138.6	182.9	170.9	113	60.9	48.5
14.1	151.2	35.9	104.4	146.5	164.7	180.6	111	57.7	54.7
20	214.5	43.7	130.8	171.9	236	210.3	80.6	67.1	59.3
28.3	303.5	23.7	89.6	192.1	290.5	232	124.5	78.6	79.3
40	429	68.4	139.3	254.6	337.4	308.6	167.3	230.8	44

Resistivity values are in Ωm

Table 3

Azimuthal resistivity values measured at Anglican Science School (ASS), Igarra survey site

a (m)	K	0°	22.5°	45.0°	67.5°	90.0°	112.5°	135.0°	157.5°
5	53.6	194.3	182.4	226.4	293.8	270	294.2	226.9	191.4
7.1	75.8	122.5	1033.5	2139.3	228.3	380.8	262.7	194.4	128
10	107.3	1834.6	73.2	121.9	247	7865.7	222.3	128.7	96.8
14.1	151.2	840.1	98	94.5	258	510.3	292.7	166.7	105.6
20	214.5	86.4	113.7	133.9	308.2	338	273.6	202	222.8
28.3	303.5	155.5	186.7	175	369.8	383.6	348	270.5	195.9
40	429	117.5	230	205	525.9	511.5	480.9	474.4	244.4

Resistivity values are in Ωm

subsequently plotted in polar and Cartesian coordinate for the different a-spacing. Representative plots are presented in Figs. 4 and 5 for want of space.

The presence of fractures with preferred or dominant strike direction results in electrical anisotropy in rocks. This electrical anisotropy is exploited by the Azimuthal Square Array Survey in the determination of subsurface fracture strike direction. Two methods of determining the dominant strike direction from the geophysical survey data were analyzed for the study area as discussed below.

4.1. *Graphical Estimation of Fracture Strike:*

Plots of apparent resistivity as a function of azimuth in polar coordinates were used to graphically estimate the dominant fracture strike orientation in the study area. Circular plots indicate electrical

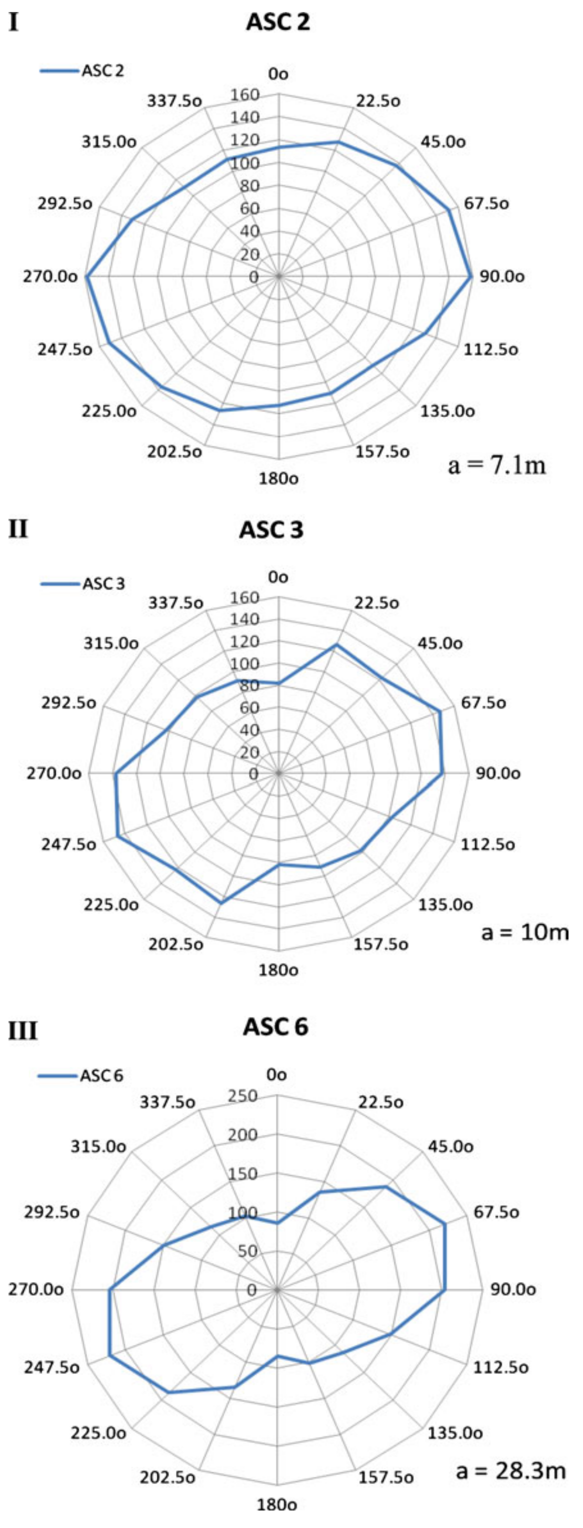

Figure 4

Representative azimuthal plots of *square array* resistivity measurements for different a-spacing. Azimuth is in degrees and in the *radial axis* while resistivity is in Ωm and in the *vertical axis*

isotropy while elliptical plots indicate electrical anisotropy. With the square array, the orientation of the fracture strike is defined and interpreted as the orientation of the minor axis of the ellipse of the polar plot. Visual inspection of the ellipse fitted to the polar plot (Fig. 6) showed that the fracture strike is approximately NNW–SSE, ranging from 130° to 175° with an average of 150° azimuth.

4.2. Analytical Estimation of Fracture Strike

Another quantitative approach for determining the dominant fracture strike orientation of subsurface fracture was attempted and compared with results obtained from the graphical method. This relies on an analysis of the Crossed Square Array data (Fig. 7). The Crossed Square Array analysis makes use of four resistivity measurements—two alpha and two beta measurement ℓ_α, ℓ_α^1, ℓ_β and ℓ_β^1 defined by:

$$\ell_\alpha = R_1$$
$$\ell_\alpha^1 = R_2$$
$$\ell_\beta = R_3$$
$$\ell_\beta^1 = R_4$$

To compute the fracture strike (θ), the relation given below is used:

$$\theta = 0.5tan^{-1}\left(\frac{(D^{-2} - C^{-2})}{(A^{-2} - B^{-2})}\right) \quad (3)$$

(Habberjam, 1975)

where A, B, C and D are defined by:

$$A = \frac{3R1}{2} + \frac{R2}{\sqrt{2}} + \frac{R3}{2} + \frac{R4}{\sqrt{2}}$$
$$B = \frac{R1}{2} + \frac{R2}{\sqrt{2}} + \frac{3R3}{3} + \frac{R4}{\sqrt{2}}$$
$$C = \frac{R1}{\sqrt{2}} + \frac{3R2}{2} + \frac{R3}{\sqrt{2}} + \frac{R4}{2}$$
$$D = \frac{R1}{\sqrt{2}} + \frac{R2}{2} + \frac{R3}{\sqrt{2}} + \frac{3R4}{2}$$

At a depth of about 18 m, corresponding to a-spacing of 40 m and well below the near surface area where weathering effects may mask resistivity readings, the Crossed Square Array survey was conducted and the following values obtained:

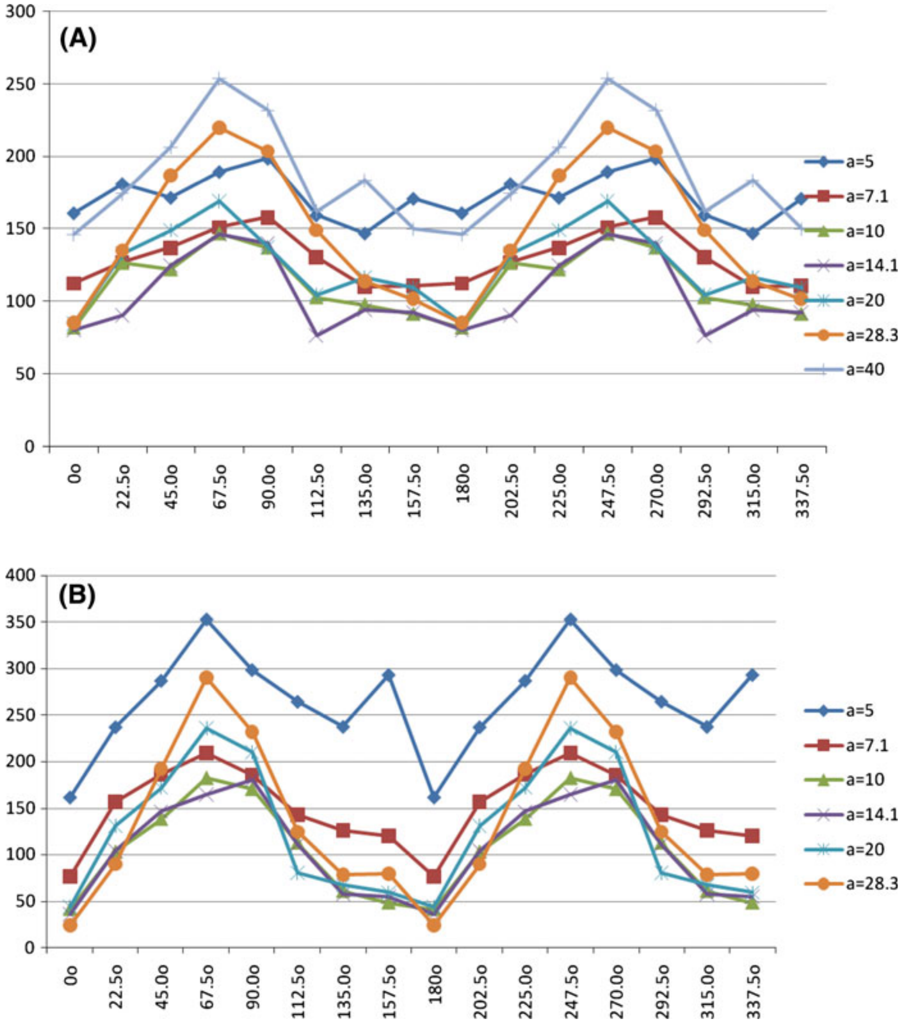

Figure 5
Plot of *square array* apparent resistivity in Ωm (on the *vertical axis*) versus azimuth in degrees (on the *horizontal axis*) for different a-spacing for Anglican Science College (**a**) and Technical and Science College (**b**) survey sites

$$\ell_\alpha = R_1 = 117.5 \quad \Omega\text{m}$$
$$\ell_\alpha^1 = R_2 = 205 \quad \Omega\text{m}$$
$$\ell_\beta = R_3 = 170 \quad \Omega\text{m}$$
$$\ell_\beta^1 = R_4 = 263 \quad \Omega\text{m}$$

It follows therefore that:

$$A = 592.2$$
$$B = 645.7$$
$$C = 642.9$$
$$D = 700.9$$

Fracture strike orientation θ is given as:

$$\theta = 0.5\tan^{-1}\left(\frac{(700.9^{-2} - 642.9^{-2})}{(592^{-2} - 645.7^{-2})}\right)$$
$$\theta = -20^{\circ}$$

The angle θ is negative, meaning that θ is in the second or fourth quadrant. In conventional trigonometry, negative angle are counted in a clockwise manner from the positive *x*-axis. The implication is that 90° is added to the absolute value of the computed angle to get the azimuth of the strike of the fractures. Hence, the azimuth of the dominant fracture strike orientation is computed as 110°.

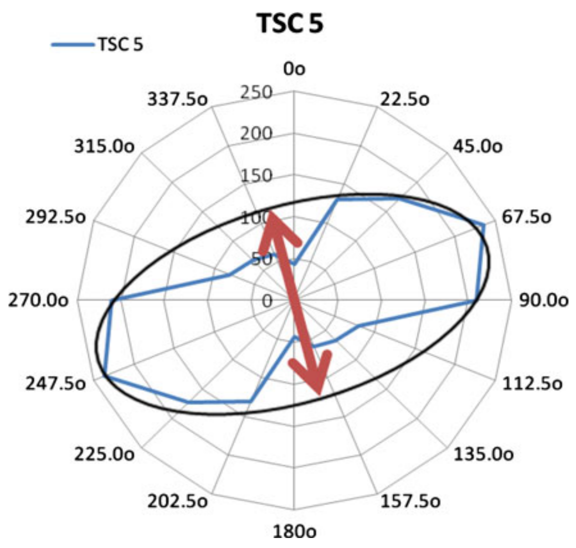

Figure 6
Representative polar plot with fitted ellipse used in determining dominant fracture strike orientation (indicated by the *arrow*)

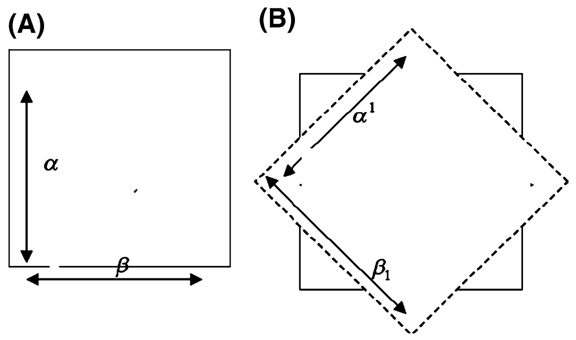

Figure 7
Illustration of the *Crossed Square Array*. **a** Shows the conventional arrangement of the square array while **b** Shows the arrangement when *two arrays* are oriented at an angle of 45° to each other (the *Crossed Square Array*) (Habberjam, 1972)

5. Result Interpretation and Discussion

5.1. Geophysical Survey Versus Geological Mapping Strike Orientation

Data collected from the Azimuthal Square Array Resistivity Survey at the study area showed a significant variation of apparent resistivity for different array orientation for all a-spacing (Tables 1, 2, 3). Variation of apparent resistivity with azimuth result when the rock mass is anisotropic and/or inhomogeneous. Anisotropy may result, generally, from the presence of fractures and/or preferential alignment of minerals or foliation in the rocks. Anisotropy can also result from other depositional processes. However, fracturing remains a major cause of anisotropy in rocks (Anderson *et al.*, 1994). Plots of Azimuthal Square Array Resistivity data showed that the data obtained at shallow depth (corresponding to a-spacing of 5 m) are relatively not well defined. This may be due to scatter caused by the electrode effect and near surface resistivity contrast. Insertion of electrodes into the ground typically causes distortion of the near surface resistivity values. This is known as the electrode effect, a form of geological noise. However, at greater depth (corresponding to greater a-spacing), the polar plots showed significant ellipticity. Assuming fractures to be the major cause of anisotropy in the rock mass, the direction of maximum apparent resistivity measured by the square array survey will be perpendicular to the dominant fracture strike direction (Habberjam, 1972). Graphical analysis of the data plot gave the dominant fracture strike orientation to be NNW–SSE with an average value of 150°. The analysis also showed that the fracture strike orientation did not change significantly with depth as all the plots have similar orientation. The results of the analytical estimation of the fracture strike orientation using the Crossed Square Array data gave a value of 110° which is also in the NW–SE direction. These results compare with data obtained from most of the outcropping fractures studied during the surface geological mapping (Fig. 8) which gave the general fracture strike orientation as N–S; however, a careful study of the fractures showed that the major and extensive fractures spanning through length of tens of meters, with significant fracture aperture all have their dominant strike direction in the NNW–SSE direction. Most of the mapped fractures in other orientation are relatively small and tight closing, spanning an average length of 3–5 m. These are located in between the major fractures, and sometimes connecting two major fractures (Fig. 9). Minor folds observed near and around the Azimuthal Resistivity Survey site have axial plain/fold axis orientation in the NNW–SSE direction (165° azimuth) also. This shows that the Azimuthal Square Array Resistivity method is capable of determining subsurface fracture strike orientation to a few degrees of values obtained

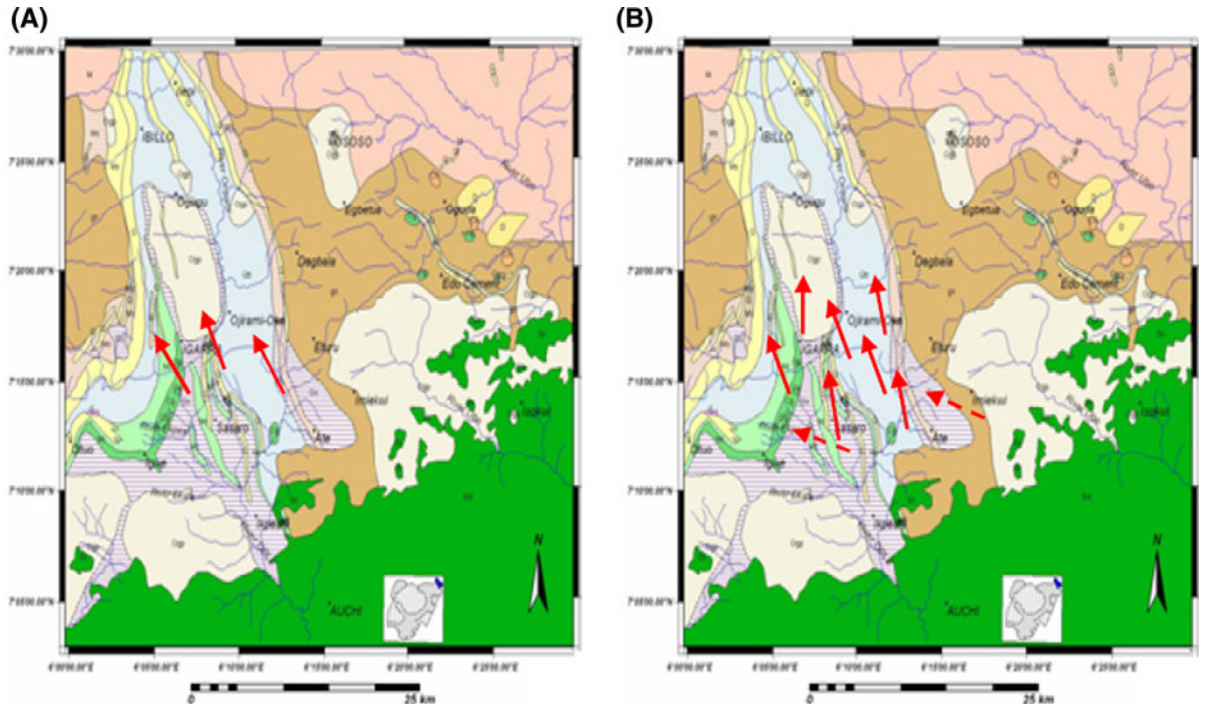

Figure 8
Geologic map of the Igarra area showing regional structural trend and dominant fracture strike orientation obtained from geophysical survey analysis (**a**) and surface geological mapping analysis (**b**). *Dashed arrows* indicate trend of minor fractures observed from outcrops. (Modified from Anifowose, 2006)

Figure 9
Surface outcrop of major fractures trending NNW–SSE and minor fractures in other strike orientation (fractures filled in with quartz veins)

from surface geological mapping. Though surface geologic mapping gives a more accurate result, some of the fractures at the surface may have resulted from secondary factors such as pressure rebounce and rock blasting/cutting especially on road cut exposures, and hence may have localized fracture strike orientation quite dissimilar from those of the subsurface fractures. However, azimuthal resistivity survey gives the averaged and weighted dominant fracture strike orientation over a large subsurface rock volume, and may not resolve the minor fractures in other orientations that are captured in the surface geological mapping analysis. This may account for the slight variation in its value compared to that of the surface geologic mapping. The marked decrease in apparent resistivity in the 0° azimuth observed in most of the polar plots in all the survey sites suggests the presence of conductive fractures in that orientation, supporting the interpretation of the results from the graphical and analytical models of fracture strikes estimation.

6. Conclusion

Fractures are seen at any rock outcrop. They are secondary structures characterized by discontinuity, and result only when the deformative force acting on the rock body overcomes the cohesive strength of the rock. The study area, Igarra, is part of the SW block of the Nigerian Basement Complex, underlain by crystalline rocks.

Surface geological mapping and geophysical mapping using the Azimuthal Square Array Resistivity method was done with the aim of characterizing the fractures (and any other structures). Data obtained from the geophysical survey showed that the rocks in the area are anisotropic with respect to their electrical properties. This anisotropic behaviour is interpreted to be due to the presence of fractures with dominant strike orientation. Analysis of the geophysical survey data gave the dominant fracture strike orientation as NNW–SSE. This corroborates with the results of the analysis of the surface geological mapping data. These fractures influences groundwater flow and contaminant transport. Therefore, information on fracture distribution and strike orientation is very vital in modeling groundwater flow and contaminant transport, planning proper waste management programs as well as Environmental Impact Assessment (EIA) analysis for the study area.

Finally, this study illustrates the satisfactory use of a non-invasive geophysical method in characterizing fractures in the subsurface especially where quality outcrops are not available or inaccessible.

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