Anisotropic Properties of Fractures in Parts of Ibadan, Southwestern Nigeria: Using Azimuthal Resistivity Survey (ARS)

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Abstract: This study investigated the groundwater potentials and anisotropic properties of fractures for sustainable groundwater development within Ibadan metropolis. Eighteen Vertical Electrical Sounding (VES) and three Azimuthal Resistivity Surveys (ARS) were conducted in an area covering about 135km^2 in northeastern part of Ibadan. Graphical interpretation of the VES data revealed the area to be underlain by three to four geo-electric layers; top soil (14.7 to 441.4 Ωm), weathered layer (2.95 to 712 Ωm), fractured bedrock (10.0 to 255 Ωm) and fresh/basal bedrock (307.6 to 2188.8 Ωm) with depth to fracture systems ranging from 15-160m. The directions of electrical anisotropy lie dominantly at NW-SE and NE-SW, while N-S and W-E are less prominent. Coefficient of anisotropy ranges between 8.79 and 1.0 and fracturing porosity varies between 1.62 and 0.01 assuming the anisotropy is due to fracturing. Result of groundwater head contouring also showed that groundwater flow is dominantly in NW-SE and NE-SW directions which possibly could be associated to fracture-controlled flow.

Key words: Anisotropy, electrical resistivity, fracture porosity, groundwater flow

INTRODUCTION

Fractures provide significant sources of water in bedrock aquifers and are also of great importance to waste disposal, groundwater 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 the complexity of groundwater flow (Taylor and Fleming, 1988). 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). The identification and characterization of fractures is important in rocks with low primary porosity (e.g., crystalline rocks) because their bulk porosity and permeability are determined mainly by the intensity, orientation, connectivity, aperture and infill of fracture systems (Skjernaa and Jørgensen, 1993; Watson and Baker, 1999).

Azimuthal resistivity survey is a modified resistivity survey in which the magnitude and direction of electrical anisotropy can be determined. Different authors have shown the usefulness of Azimuthal Resistivity Survey (ARS) in determining the principal direction of electrical anisotropy (Leonard-Mayer, 1984; Taylor and Fleming,

1988; Ritzi and Andolsek, 1992; Skjernaa and Jørgensen, 1993; Al Hagrey, 1994; Odoh, 2010). Typically, any observed change in apparent resistivity with azimuth is interpreted as invocative of anisotropy (generally fracture anisotropy). It is often assumed that the principal directions of hydraulically conductive fracture may be inferred from the measured electrical anisotropy (apparent resistivity (ρa) as a function of azimuth and depth), since both current flow and groundwater are channelled through fractures in the rock.

In this study, we report on the capabilities of azimuthal resistivity survey to:

- Determine the characteristic fracture patterns
- Estimate hydraulic parameters of the subsurface fractured Basement Complex
- Compare and integrate the determined fracture orientations to groundwater head-contouring thereby providing a useful methodology to characterize subsurface fractures

Location and geology of the area: The study area lies within latitudes 7º21′ N-7º25′N and Longitude 3º55′ E-4º00′ E (Fig. 1) and falls in the northeastern part of Ibadan. Ibadan is the third largest city in Africa with an estimated population of about 1.3 million, growing rapidly with industries and residential houses being

Corresponding Author: G.O. Ogungbesan, Department of Earth Sciences, Ladoke Akintola University of Technology, Ogbomoso, Nigeria, Tel.: +234-8053432408
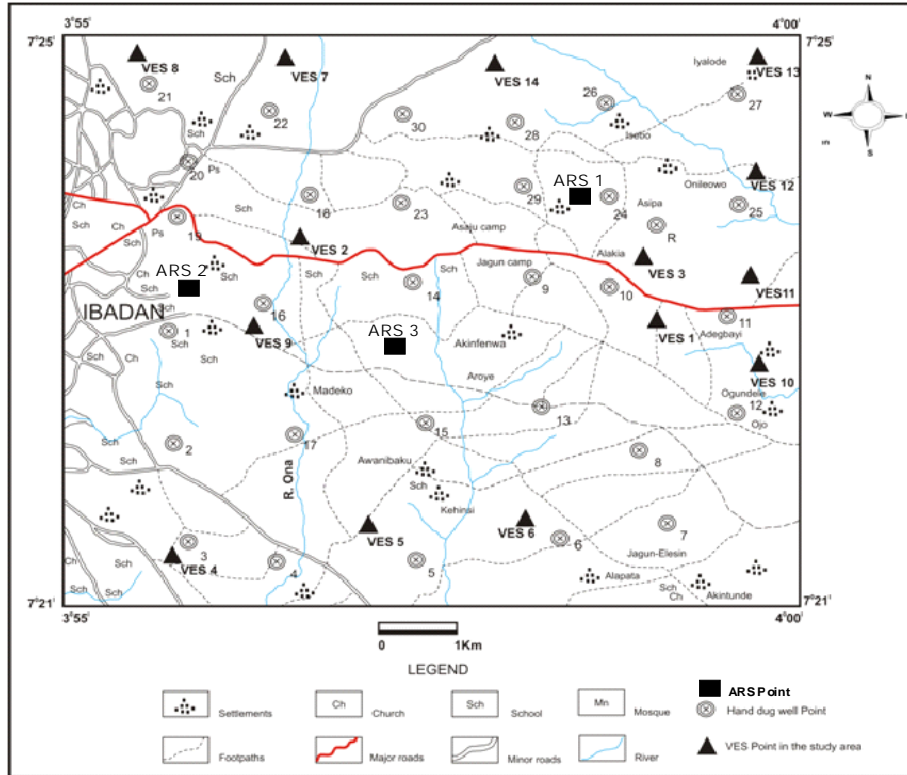
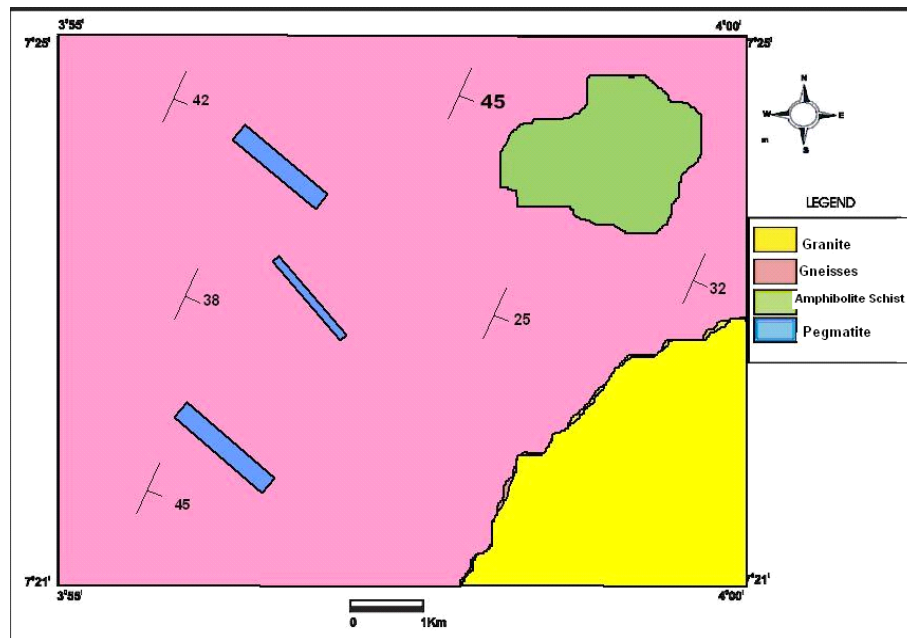Fig. 1: Map of the study area showing sampling locations

Fig. 2: Geological map of the study area

constructed at a very fast rate making the demand for water to have increased tremendously. Water supply is largely scarce with many depending on the hand-dug wells and stream for their domestic water supply which are insufficient, highly fluctuating and prone to contamination.

Ibadan lies within the Basement Complex terrain of southwestern Nigeria which comprises of gneiss, migmatite and metasediments of Precambrian age which have been intruded by series of granitic rocks (Rahaman, 1988). The study area is underlain by three main rock types: gneisses, schists, and granite being cross cut by pegmatites (Fig. 2). Gneiss which is the dominant rock type in the area has low relief and occur as migmatite gneiss and banded granite gneiss. The schists occur at the northeastern part as low lying outcrops and cover a larger part of this region. The rocks are highly weathered and fractured in most cases and possess various visible structures.

METHODOLOGY

Electrical resistivity method has been observed to be the most tremendous technique for groundwater delineation among other techniques especially in the Basement Complex terrain. One of the primary problems of investigating groundwater potential in crystalline rocks is locating the fracture network. 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 resistivities measured as a function of azimuth. When apparent resistivities in different directions are plotted as radii, they generate anisotropy figures, which is an ellipse. The major axis of the apparent resistivity ellipse coincide with the strike of the fracture, while the true resistivity parallel to the fracture is equivalent to the minor axis of the ellipse (Taylor and Fleming, 1988; Skjernaa and Jørgensen, 1993).

Three Azimuthal Resistivity Surveys (ARS) were carried out at different locations within the study area (Fig. 1) with ABEM SAS-1000 Terrameter using schlumberger electrode configuration expanded about a center point. The current electrode spacing (AB/2) having a maximun spread of 200m and potential electrode spacing (MN/2) were rotated about a center point at each location and measurement were made in 45° increments (i.e., 0°, 45°, 90°, 135°) which are N-S, NE-SW, E-W and SE-NW directions. Vertical electrical sounding (VES) were performed at eighteen other locations to determine depth to the fractured bedrock. The entire survey was conducted between September 2010 to March 2011.

The data obtained were plotted against the electrode spacing on bilogarithm coordinates and a preliminary interpretation was carried out using partial curves matching involving two-layer master curves and the appropriate auxiliary charts of Rijkswaterstaat (1975). The layered earth model thus obtained, served as input for an inversion algorithm, WINRESIST, as a final stage in quantitative data interpretation.

The apparent resistivity measured along different azimuths for a given AB/2 separations at each location were plotted along their corresponding azimuths. Lines of the resistivity of the same value along different azimuths were joined together, thus resulting in a polygon. A set of such polygons obtained corresponding to different AB/2 separations is known as a polar diagram or anisotropy polygon. For an isotropic homogeneous formation, this polygon will assume a circular shape. Any deviation from a circle to an ellipse is indicative of anisotropic nature of the rock formation (Mallik *et al.*, 1983; Busby, 2000; Senos Matias, 2002).

Fracture porosities associated with tectonic fracturing of rocks were estimated using the expression derived by Lane *et al.* (1995):

$$\phi = \frac{3.41 \times 10^4 (N-1)(N^2-1)}{N^2 C (\rho_{max} - \rho_{min})} \tag{1}$$

$$\lambda_a = \frac{\rho_{a1}}{\rho_{a_t}} = N \tag{2}$$

Φ_f = fracture porosity; N is the vertical anisotropy related to the co-efficient of anisotropy λ_a as shown in Eq. (2), ρ_{max}-maximum apparent resistivity; ρ_{min}-minimum apparent resistivity; $\rho_a t$ and $\rho_a l$ are, respectively, the apparent resistivity transverse and longitudinal to the direction of the fracturing; and C = specific conductance of groundwater in microsiemens per centimeter (µs/cm). The specific conductance of groundwater from boreholes and hand-dug wells in the study area averaged 206 µs/cm.

RESULTS AND DISCUSSION

The results of apparent resistivity obtained at different azimuths and depths are presented in Table 1. Measured apparent resistivities were found to vary with orientation of the arrays at each depth. The observed changes in apparent resistivity (pa) with azimuth were 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.

The quantitative and qualitative interpretation of the eighteen VES conducted at different locations revealed the area to be underlain with a range of three to four geo-electric layers: topsoil, weathered bedrock, fractured bedrock and fresh bedrck with the depth to fractured rock ranging from 15-160m. Some typical graphical plots of the VES and the geo-electric layers is show in Fig. 3.

To minimize the possible effect of overburden, the ARS data were analyzed by plotting the apparent
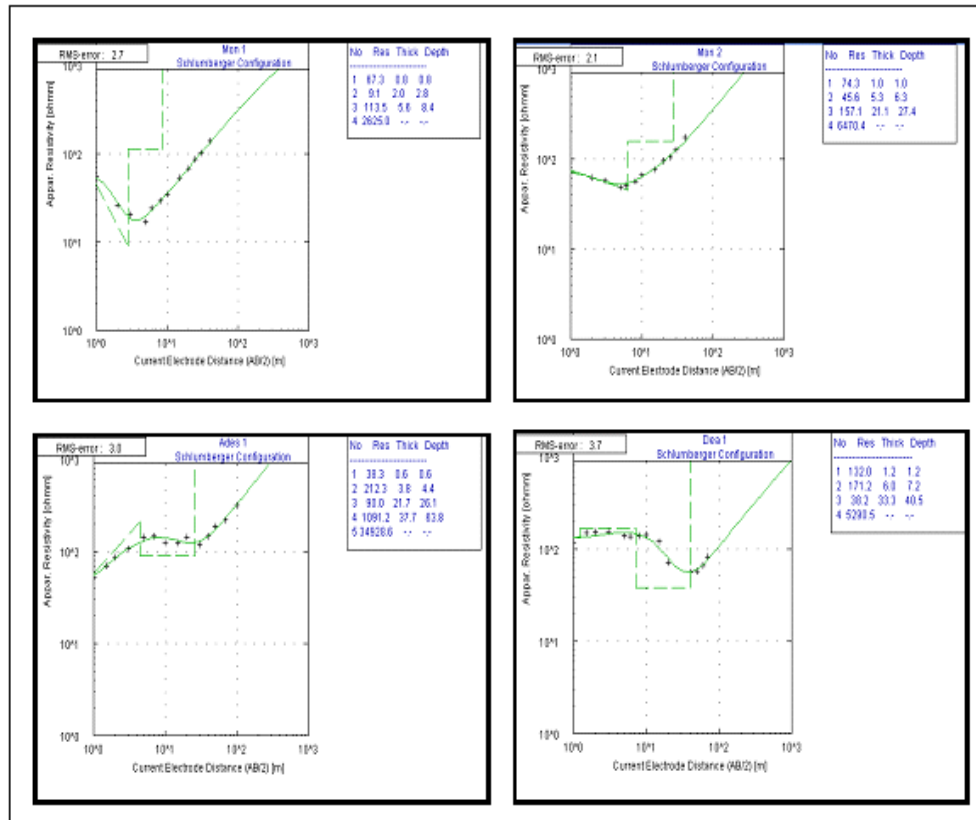
Fig. 3: Examples of some smoothed VES curves and results of interpretation

Table 1: Apparent resistivity data at ARS 1, 2 and 3

	Apparent resistivity (m-m)											
	ARS1				ARS 2				ARS3			
AB/2 (m)	0°	45°	90°	135°	0°	45°	90°	135°	0°	45°	90°	135°
1	173.6	152.2	151.3	168.4	124.4	133.8	135.3	124.4	115.0	105.9	103.1	110.5
1.5	184.8	152.9	168.8	174.9	171.2	193.7	191.1	163.1	115.6	148.8	143.4	159.0
2	200.5	153.4	163.7	178.8	214.7	243.3	240.2	201.0	147.0	184.0	179.1	198.3
3	187.3	166.3	171.3	165.6	139.4	320.0	324.5	293.0	250.5	242.8	229.6	260.4
5	180.0	180.4	189.4	199.3	418.5	469.7	459.9	386.2	274.6	319.3	315.5	375.7
5	118.4	193.6	204.8	194.3	398.8	446.2	444.8	405.4	281.7	313.8	330.6	370.4
7	130.2	188.5	195.7	199.1	458.0	545.6	517.3	456.4	425.8	378.4	382	451.8
10	48.5	144.5	168.7	184.2	510.2	605.2	589.3	480.0	521.7	407.4	413.9	45.1
15	150.3	126.3	150.8	187.7	611.6	571.0	615.0	539.6	557.5	455.5	388.8	491.2
20	163.0	127.4	164.9	185.0	545.0	596.8	585.8	529.3	566.6	477.2	414.3	542.3
30	172.3	125.8	165.2	173.2	546.5	576.2	598.2	609.8	530.1	452.1	415.7	480.8
40	170.3	63.9	720.0	108.2	495.7	601.0	413.8	464.9	522.5	406.5	394.6	431.4
50	178.3	100.6	144.5	884.2	494.9	605.7	461.4	450.6	413.0	435.7	419.6	727.2
70	131.2	102.7	148.1	109.6	482.2	502.2	377.9	374.5	307.4	351.7	320.0	378.8
100	252.2	105.9	141.2	103.8	413.1	426.7	337.2	273.1	237.3	260.4	235.1	292.5
120	201.1	118.5	147.0	118.3	375.1	419.9	326.9	94.35	261.6	290.6	255.8	289.6
150	140.6	19.3	188.0	102.8	245.6	299.5	260.6	285.3	240.0	247.8	312.5	301.3
200	188.6	156.6	103.0	563.4	228.8	199.4	254.0	445.5	264.2	156.8	301.4	331.6

resistivity against azimuths at depths ranging from 20-200 m on azimuthal polar diagram (Fig. 4-6). The survey identified NW-SE (135°), NE-SW (45°), N-S (0°) and W-E (90°) trends as the electrical anisotropy direction in the study area. These multiple structural trend observed in the

anisotropy figures may be a result of intersection of joints: NW-SE (135°) and NE-SW (45°) trends predominate in the study area.

To further support the ARS interpretation, groundwater hydraulic head data in boreholes and hand-
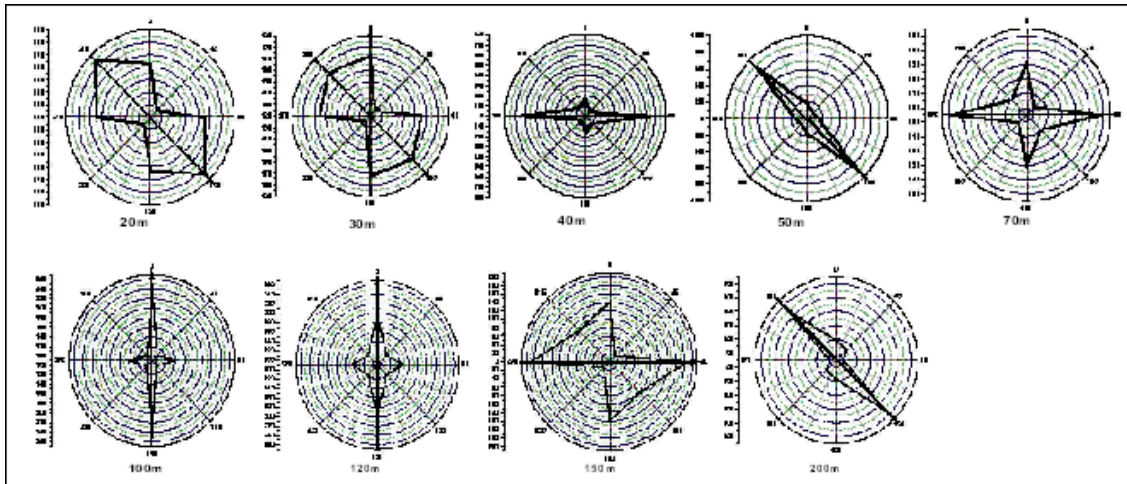
Fig. 4: ARS 1 polar plots of the apparent resistivity against azimuth at depths
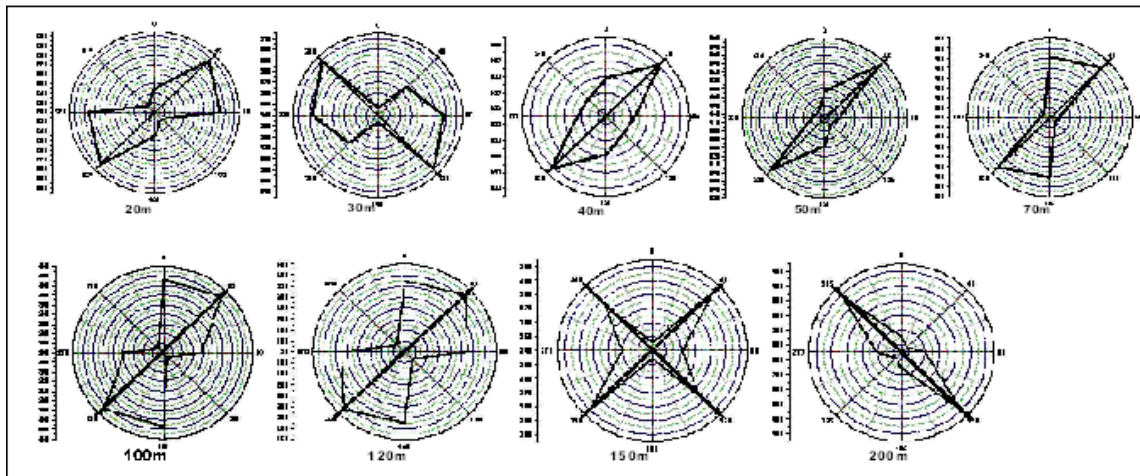

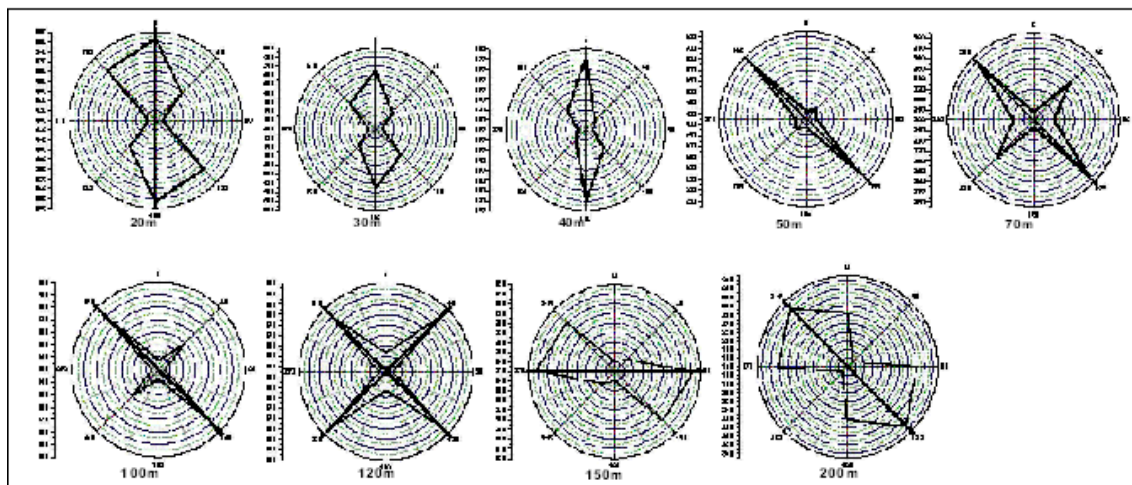Fig. 5: ARS 2 polar plots of the apparent resistivity against azimuth at depths

Fig. 6: ARS 3 polar plots of the apparent resistivity against azimuth at depths
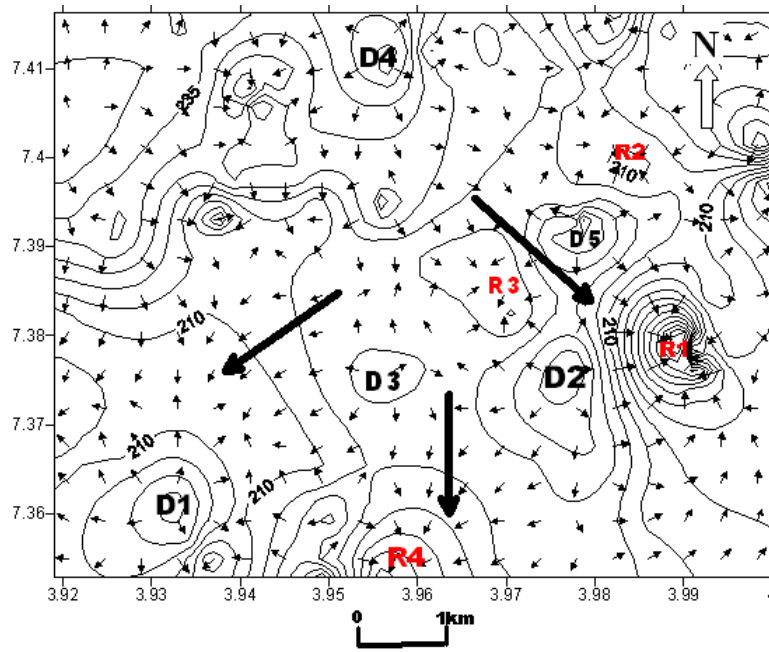
Fig. 7: Groundwater head contour map showing flow direction.R1, R2, R3, R4 - indicate recharge zones; D1, D2, D3, D4, D5- indicate discharge zones.

Table 2: Characteristics fracture parameters at each site obtained from analysis of Azimuthal resistivity data obtained from the study area

Location	AB/2 (m)	Major strike direction	Coefficient of anisotropy (λ)	True resistivity (ρ_x)	Fracture porosity (Φ_f)
ARS 1	20	135° (NW-SE)	1.45	127.4	0.68
	30	135° (NW-SE)	1.38	125.8	0.62
	40	90° (W-E)	4.22	170.3	0.77
	50	135° (NW-SE)	8.79	100.6	1.62
	70	90° (W-E)	1.13	131.2	0.10
	100	0° (N-S)	1.79	141.2	0.60
	120	0° (N-S)	1.37	147.0	0.34
	150	90° (W-E)	1.34	140.6	0.15
	200	135° (NW-SE)	3.59	156.6	0.86
ARS 2	20	45° (NE-SW)	1.13	529.3	0.07
	30	135° (NW-SE)	1.02	596.8	0.02
	40	45° (NE-SW)	1.28	469.9	0.10
	50	45° (NE-SW)	1.34	450.6	0.16
	70	45° (NE-SW)	1.34	374.5	0.20
	100	45° (NE-SW)	1.56	273.1	0.36
	120	45° (NE-SW)	4.45	94.35	1.67
	150	45° (NE-SW)	1.05	285.3	0.01
	200	135° (NW-SE)	2.23	199.4	0.66
ARS 3	20	0° (N-S)	1.37	414.2	0.19
	30	0° (N-S)	1.28	414.7	0.15
	40	0° (N-S)	1.32	394.6	0.18
	50	135° (NW-SE)	1.66	437.7	0.22
	70	135° (NW-SE)	1.08	351.7	0.02
	100	135° (NW-SE)	1.23	237.1	0.24
	120	135° (NW-SE)	1.00	289.6	0.01
	150	90° (W-E)	1.30	240.0	0.28
	200	135° (NW-SE)	2.11	156.8	0.82

dug wells were collected and used to generate the groundwater flow contour map (Fig. 7). This map shows the various directions of groundwater flow establishing the dominant directions to be in NW-SE and NE-SW.

The estimated values of coefficient of anisotropy and fracture porosity are generally found to increase in magnitude with depth of investigation indicating the fractures opening with increasing depth. The coefficient of anisotropy varies between 8.79-1.00 and the fracture porosity varies between 1.62-0.01 (Table 2).

CONCLUSION

The azimuthal resistivity survey has been used to determine and characterized the anisotropic properties of fractures in northeastern part of Ibadan, southwestern Nigeria for evaluation of groundwater potential and flow within the area. Measured apparent resistivity was found to varied with orientation of arrays and depth and this was interpreted to be an indicator of fracture anisotropy. The interpretation of VES data indicate the area to be underlain by three to four geo-electric layers with the depth to fractured basement ranging from 15-160 m. The azimuthal polar diagrams plotted for apparent resistivity against azimuth at depths ranging from 20-200 m revealed NW-SE and NE-SW as the dominant electrical anisotropy directions while N-S and W-E directions are less prominent.

ACKNOWLEDGMENT

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