IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 9, Issue 6 Ser. I (Nov. – Dec. 2021), PP 52-60
www.iosrjournals.org

Hydrogeological Characterisation of Subsurface Fractures from Azimuthal Resistivity Surveys: A Case Study of Gonin Gora, Kaduna, Northwestern Nigeria

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Abstract

Background: *Study for the hydrogeological characterisation of fracture patterns in the rocks of Gonin Gora northwestern Nigeria was carried out using geological, hydrogeological and azimuthal direct current electrical resistivity methods.*

Materials and Methods: *Fracture orientations, width and spacing were studied on rock outcrops in the area. Water table, total well depths and ground elevation were measured in 17 open wells. Azimuthal electrical resistivity measurements were carried out along four azimuths (0^o, 045^o, 090^o and 135^o) at three different stations. The field-measured fracture orientations were plotted on polar plots to determine the principal fracture direction. Groundwater level elevation map was produced to deduce the groundwater flow direction. The results of the resistivity surveys were plotted as anisotropy polygons from where the orientations of the subsurface fractures were inferred which could help to correlate with the fractures observed on the outcrops.*

Results: *The rocks are predominantly migmatite-gneisses and metasediments. Geological mapping indicates the principal fracture orientation in the area is NE-SW with other fracture systems oriented in N-S, NW-SE and E-W directions. This agrees well with the inferred fracture directions from the anisotropy polygons. Groundwater level elevation map shows that groundwater flows from southwest to northeast in the area which shows strong influence of fracture orientation on groundwater flow. The plots of variation of coefficient of anisotropy with depth generally open with depth from about 30 m downwards, suggesting intense fracturing at depth. This indicates that boreholes drilled to beyond 30 m have good prospects of moderate to good yields, characteristic of Basement aquifers.*

Key words: *Gonin Gora, azimuthal, groundwater, fracture orientation, anisotropy*

Date of Submission: 20-11-2021 Date of Acceptance: 05-12-2021

I. Introduction

Groundwater occurrence in Nigeria is controlled by geology in which the country is underlain by Basement complex rocks and sedimentary basins in roughly equal proportions. Basement complex rocks are found in the west, north-central and the southeast blocks of the country. These rocks can form local aquifers if they are sufficiently weathered and /or fractured. Groundwater occurs in Basement rocks in the thin, discontinuous mantle of weathered rocks or in the joint and fracture systems in the unweathered basement which provide secondary reservoirs. This makes these aquifers have low groundwater potential compared to the sedimentary basins.

Despite their poor hydrogeological characteristics, Basement rocks are still important in groundwater development in Nigeria because they provide a lot of water for the needs of about 50% of the population in country. The spatial variation in the degree of weathering and fracturing of Basement rocks across the country implies that groundwater potential varies from place to place. Well yield and groundwater flow direction in fractured rocks is directly related to the density, frequency, orientation and inter-connection of structural features at depth[1], and there is therefore, the need to carry out proper investigations to identify structural elements and their orientation before siting boreholes.

Surface geological mapping of structural elements is limited only to areas where there are rock outcrops. Remotely sensed data may suffer poor quality and inaccurate interpretation and correlation with features on the ground because of such factors as masking effect of dense clouds, thick vegetation cover and position fixing errors of remote sensing equipment[1]. Hence surface geophysics offers a good prospect for mapping subsurface structural elements.

Subsurface structural elements such as fractures, faults, joint systems and layering exhibit, what in geophysical lexicon, are known as electrical anisotropy. According to Taylor and Fleming[2], a rock is said to be electrically anisotropic if the value of a vector measurement of its resistivity varies with direction. Electrical resistivity is a measure of a material's resistance to the flow of electric current. What is measured in the field is known as apparent resistivity (ρ_a) value which is related to rock type and water content. The apparent resistivity value is also affected by location and spacing of electrode array (which determines depth of investigation), as well as directional variation in the electrical property of the medium (electrical anisotropy). In a horizontally stratified system the plane of anisotropy is generally parallel to the surface. In dipping layered rocks, as well as fractured rock units the plane of anisotropy is not parallel to the surface, and the measured apparent resistivity will be dependent on orientation[3]. The existence of fractures in rocks can potentially increase hydraulic conductivity by several orders of magnitude[4].

To effectively map fracture orientations in the subsurface for groundwater flow directions the anisotropic resistivity image of the subsurface becomes indispensable. Azimuthal or rotational resistivity survey is embarked upon to measure subsurface electrical anisotropy. This method utilizes the conventional electrical resistivity equipment and the electrode array is rotated about a fixed central point. In the conventional electrical resistivity survey with collinear set of electrodes most of the current paths sample the subsurface below the survey line. By varying the azimuth of the survey line we can measure directional variations in electrical properties of the subsurface because line azimuths that are perpendicular to water-filled fractures exhibit higher resistivities than those that are parallel to those fractures[5]. The azimuthal survey generates an apparent resistivity ellipse from which the properties of the subsurface joint system can be determined[2].

Since research into the study of anisotropic nature of rocks using azimuthal electrical resistivity survey started many workers have applied this method with results showing very good correlation between observed field fracture orientations and electrically measured anisotropic orientations. 4 carried out a study on determining subsurface fracture characteristics from azimuthal resistivity surveys at Nsawam, Ghana. 3 used the azimuthal square array direct current resistivity measurement to determine the presence and azimuth of fractures at a location near the southwest corner of the Nevada Test Site in Nye County, Nevada and conclude that the relatively thick sequence of alluvial sediments at the site makes the contact between the alluvium and the tuff difficult to resolve using the square array method and that the conventional collinear Wenner or Schlumberger array methods would instead be a better choice. 6 applied electrical resistivity anisotropy in geological mapping in Odo Ara, West Central Nigeria. Similarly, 7 used integrated resistivity sounding and anisotropy for hydrogeologic investigation of Alakuta-Apete area of Ibadan Southwestern Nigeria. 1 also did an evaluation of resistivity anisotropy of parts of Ijebu Igbo, southwestern, Nigeria using azimuthal resistivity survey (ARS) method. 5 conclude, from the study on azimuthal resistivity sounding with the symmetric Schlumberger and the Alpha Wenner Arrays to study subsurface electrical anisotropy variation with depth that the Schlumberger configuration is more sensitive to anisotropy than the Wenner configuration. 8 used panoramic azimuthal Schlumberger vertical electrical sounding for fracture orientation and anisotropy quantification at Federal University of Technology, Akure, Nigeria. From the foregoing, it is clear that azimuthal electrical resistivity survey can be effectively used to study and characterize fracture systems which are important in weathering of rocks and groundwater flow, especially in the Basement terrains such as we have in Gonin Gora, the area of this study.

The Gonin Gora, is a fast developing satellite settlement in Chikun Local Government Area on the outskirts of Kaduna metropolis in Kaduna State and is underlain by Basement rocks. Households, commercial and industrial concerns depend on groundwater for their water supply due to the absence of public water supply. There have been sporadic and uncoordinated efforts to exploit the groundwater resources of the area due to the high influx of people. The residents have been lucky so far because most of their wells and boreholes are productive. But as more and more people settle in the area and are abstracting groundwater from the same aquifer, there is likelihood of water shortage in the future due to over exploitation. Blind and random location of boreholes then may not produce the desired result as water in shallow aquifers may no longer be available. Locating suitable points for groundwater abstraction will be greatly enhanced by a proper understanding of the fracture patterns and degree of weathering of rocks which are essential for groundwater occurrence in Basement terrains. There is no any hydrogeological study of the area available. The aim of this study therefore, is to employ a combination of geological mapping of structural elements and azimuthal resistivity survey to locate, characterize and identify directions of fractures; and hydrogeological studies to understand the groundwater system and flow direction in the study area. This study will serve as baseline information for further hydrogeological study in the area.

II. Materials and Methods

Location, geology, climate and vegetation of the study area: Gonin Gora is located in Chikun Local Government Area on the outskirts of Kaduna metropolis. The community straddles the Abuja-Kaduna expressway. The study area lies approximately within latitudes 10^o 23'N and 10^o 26'N and longitudes 7^o 21'E and 7^o 24'E covering about 30 km^2 (figure 1).

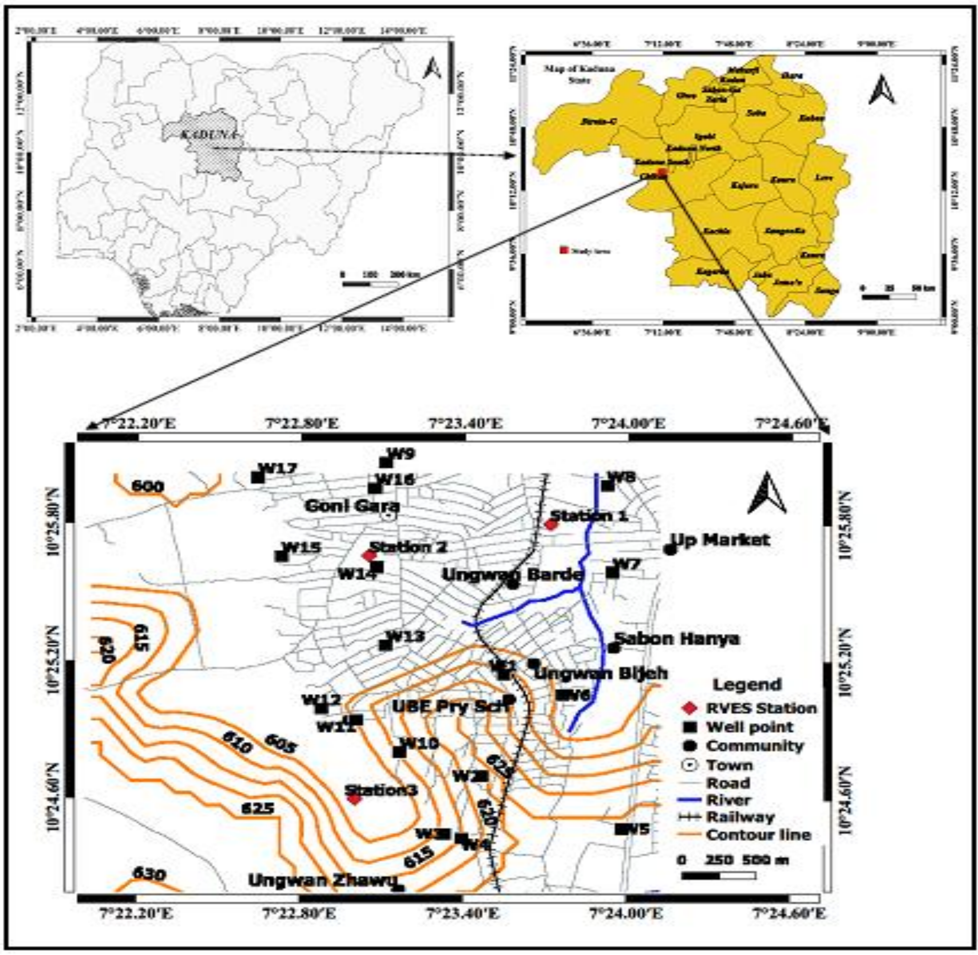


Figure 1: Location map of the study area

The geology of the study area (figure 2) is predominantly migmatite-gneiss complex and metasediments consisting of schist, quartzite and pegmatite, trending approximately NNW-SSE where they outcrop and capped in places by thick lateritic crust which are sometimes consolidated at the surface and weathered into lateritic nodules mixed with silty and sandy clays.

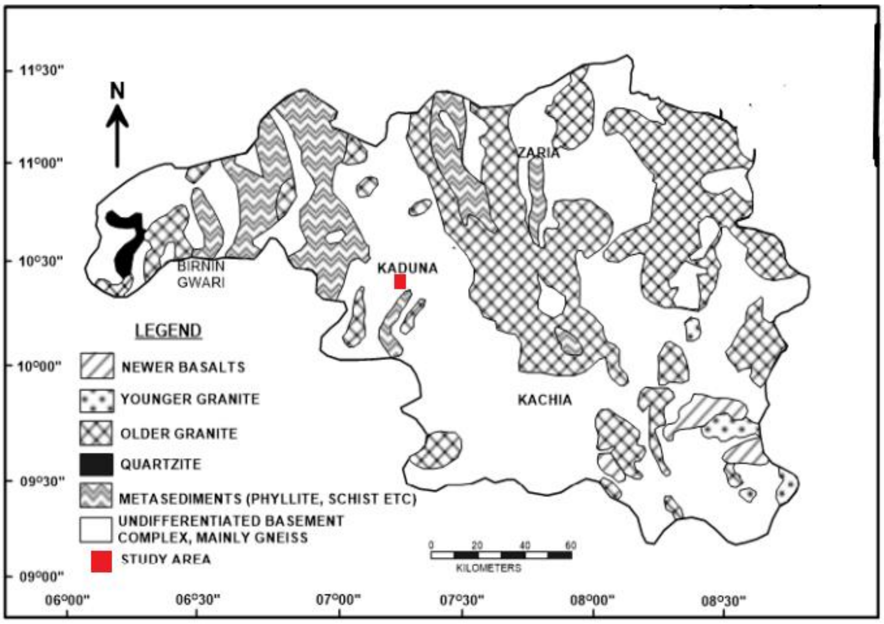


Figure 2: Generalised geological map of Kaduna State (Modified after 9)

The study area is within the tropical Savannah climate with distinct dry and wet seasons. The dry season occurs between October and April while the wet season is between May and September. These two seasons reflect the influences of tropical continental and equatorial maritime air masses which sweep over the entire country. The rainy season which starts around May/June is characterised by initial intermittent severe thunderstorms, becoming more regular in the months of July, August, and early September. Such rains ease out and cease by mid-October. There is a cool dry spell in the months of December and January when the dusty and dry harmattan winds of the north-easterly type sets in.

Vegetation in the area is of typical guinea savannah, characterised by sparse shrubs and interrupted by large isolated trees. There is more continuous grass cover in the rainy season. Cultivation of cereals and vegetable is practiced in the area.

Procedure methodology*:* Structural elements such as fractures and veins observed on the few outcrops in the study area were studied in terms of strike direction, width and mean fracture spacing. The strike directions were then plotted on a rose diagram to determine the principal strike direction of these structures. The fracture width ranges between 5 mm and 10 mm, while the mean fracture spacing ranges between 10 cm and 50 cm.

Water table and total well depths were measured in seventeen open wells in the study area. The geographic coordinates and the ground elevation above mean sea level of each well were determined using the ***eTrex Garmin 30X*** Global Positioning System (GPS). The well locations are as shown in figure 1 above. The difference between the ground elevation and the water table gives the groundwater head elevation in wells which were then contoured using ***Surfer 10*** software to give information on the groundwater flow direction.

Three different stations were occupied (figure 1 above) where twelve radial vertical electrical soundings (RVES) were conducted using the Japanese ***McOHM-EL*** resistivity meter powered by a 12 volts rechargeable battery, to identify and characterise the directional properties of anisotropic rock mass in the study area. The soundings involved the measurements of electrical resistivity along four azimuths, namely; 0^{o}, 045^{o}, 090^{o} and 135^{o} about a central fixed point (figure 3) using the Schlumberger configuration with a maximum current electrode spacing AB/2 of 60 m.

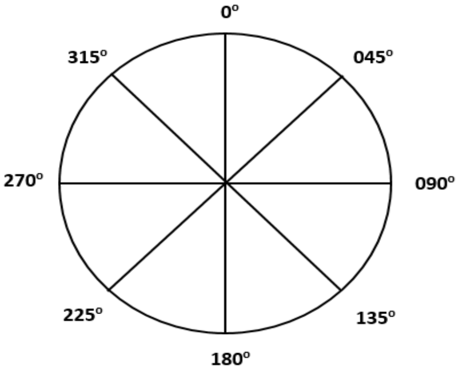


Figure 3: Azimuthal profiles used for field data collection

The recorded apparent resistivities (measured in Ohm-m) for all electrode spacings were plotted along their respective azimuths for each depth of investigation on a polar diagram in order to observe the correlation between the field-measured structural direction and the plotted anisotropy polygon direction. The resistivity points along different azimuths were joined together, giving rise to a polygon 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 formation[10]. It was observed that an ellipse fitted better to the plotted polygons than a circle, hence the best-fit ellipse was fitted to each anisotropy polygon. To describe and quantify this anisotropy two characteristics of the best-fit ellipse are important: these are the orientation of the major or longest axis of the ellipse and the anisotropy parameter. The orientation of the major or longest axis of the best-fit ellipse to the anisotropy polygon gives the strike direction of the fracture if collinear configuration like Schlumberger array is used. If square-array configuration is used the direction of the fracture is perpendicular to the maximum resistivity value (Ogunbo *et al.,* 2018). The length of the major axis is numerically equivalent to the transverse resistivity ρ_{max} which is the apparent resistivity measured across the fracture while the length of the minor axis is numerically equivalent to the longitudinal resistivity ρ_{min} which is the apparent resistivity measured along the fracture. Therefore, the anisotropy parameter, i.e. the coefficient of anisotropy, λ, calculated from each best-fit anisotropy polygon is the root of ρ_{max} / ρ_{min} [11].

i.e $$\lambda = \sqrt{\rho_{max}} / \rho_{min} \quad (1)$$

III. Results and Discussion

Structural elements

The study of fractures on rock outcrops in the study area indicates vertical to subvertical fractures with lengths ranging between 50 cm and 80 cm, width ranging between 5 mm and 10 mm, and the mean fracture spacing ranging between 10 cm and 50 cm. Thirty-seven percent (15) of the fractures have orientation in NE-SW direction, 22% (9) have orientation in the N-S direction, 17% (7) are oriented in the NW-SE direction while 12% (5) are oriented in the NNE-SSW and 12% (5) in E-W directions. The principal strike direction is NE-SW as depicted in the Rose diagram (figure 4) below.

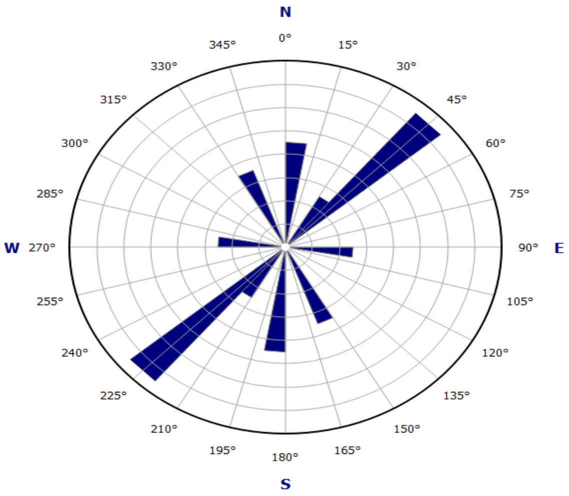


Figure 4: polar plot of fracture orientations in Gonin Gora

Hydrogeological investigation

Water table measured in seventeen open wells in the study area ranges between 2.30 m and 10.95 m while total well depth ranges between3.80 m and 12.65 m (table 1). This shows that these wells tap water from shallow aquifers in the study area.

Table 1: Result of groundwater level measurement in Gonin Gora

S/N	Well code	Lat (N)	Long (E)	Total well depth (m)	Water table (m)	Ground elevation (m)	Groundwater elevation (m)
1	W1	10.41907	7.39243	8.86	7.70	592.81	585.11
2	W2	10.41171	7.391093	6.71	5.05	600.13	595.08
3	W3	10.40749	7.38884	6.90	5.65	599.83	594.18
4	W4	10.40715	7.389887	7.15	5.15	598.93	593.78
5	W5	10.40789	7.399708	9.42	6.55	602.83	596.28
6	W6	10.41758	7.396042	7.14	4.15	574.32	570.17
7	W7	10.42652	7.399068	7.60	4.50	542.30	537.80
8	W8	10.43285	7.398698	12.20	4.44	481.09	476.65
9	W9	10.43446	7.3852	12.32	10.95	588.79	577.84
10	W10	10.41341	7.38608	8.00	6.14	599.62	593.48
11	W11	10.41571	7.383418	7.70	5.12	579.22	574.10
12	W12	10.41654	7.38131	7.80	6.15	582.42	576.27
13	W13	10.4212	7.38519	7.40	5.40	589.31	583.91
14	W14	10.42683	7.384653	12.65	10.60	592.90	582.30
15	W15	10.4276	7.3788	3.80	2.30	606.60	604.30
16	W16	10.43256	7.384503	10.60	7.10	590.49	583.39
17	W17	10.43334	7.377327	5.72	3.98	561.29	577.31

The groundwater level elevation map (figure 5) shows that the groundwater flows from the southwest to the northeast direction in the study area. This shows that groundwater flow is controlled by the fracture pattern since the principal direction of fracture strike as observed on the outcrops is NE-SW (figure 4 above). Groundwater is recharged in the western and southwestern parts around Gidan Boka and Government Secondary School areas and is discharged around Ungwan Barde in the northeastern part of the study area. Figure 6 shows groundwater elevation model. The peaks in the model represent higher hydraulic heads which coincide with recharge areas from where groundwater flows to areas at lower hydraulic head which represent discharge areas.

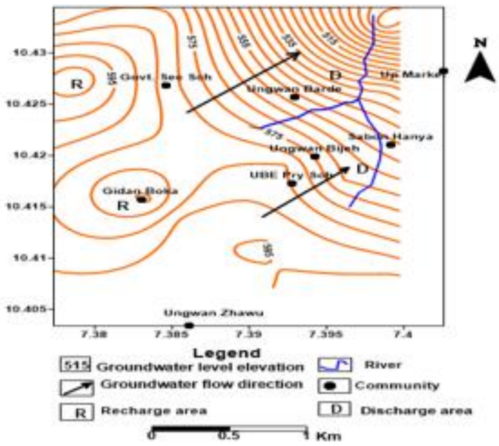


Figure 5: Water level elevation map for Gonin Gora

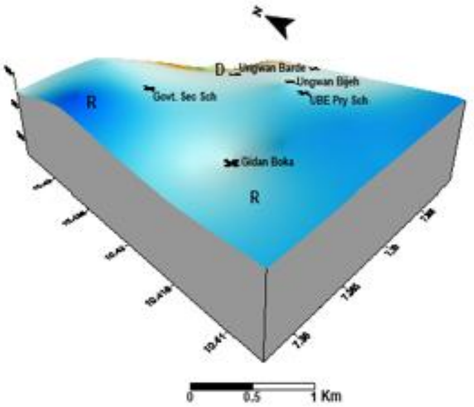
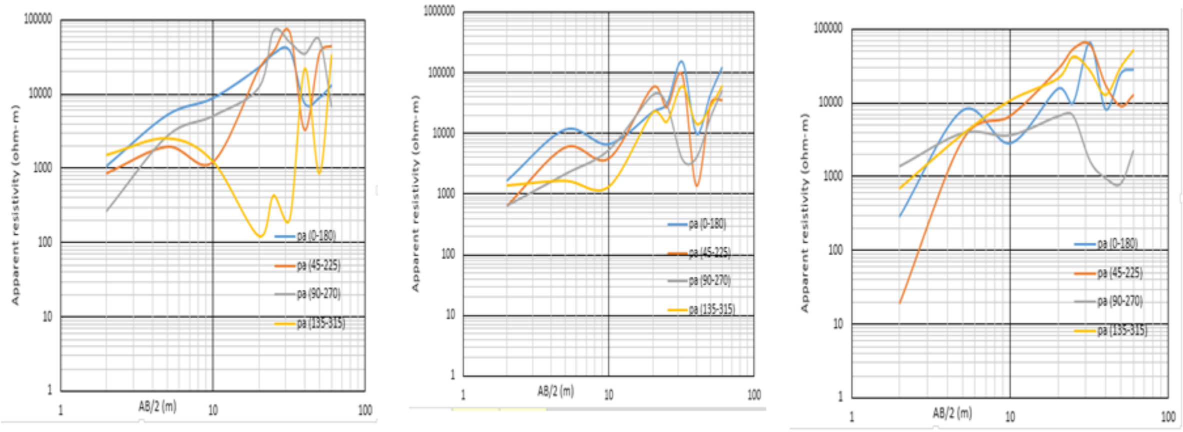


Figure 6: Groundwater digital elevation model for Gonin Gora

Geophysical investigation

Plots of apparent resistivity values which were calculated along each profile and plotted against current electrode spacing AB/2 on log-log graph are presented in figure 7 (a-c). The geometry of these plots reveal that indeed anisotropy exists in the study area as the values of apparent resistivity vary with azimuth at each of the survey stations.

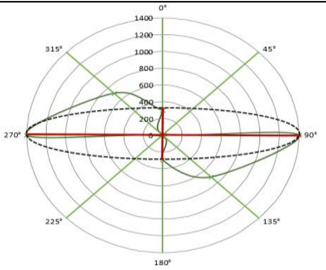


(b) Station 1 (a) Station 2 (c) Station 3

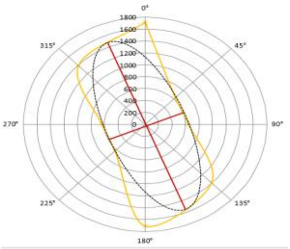
Figure 7: RVES curves in Gonin Gora

Anisotropy polygons plotted for apparent resistivity values for each depth of investigation AB/2 ranging from 2 m to 60 m for the three survey stations are presented in figure 8. The major axis of the best-fit ellipse to each polygon gives the principal strike direction of fracture. It is observed from figure 8 that the fracture system seems to have the same orientations at each depth of investigation from 2 m up to 20 m at all the three survey points, but after this depth, the fractures appear to be oriented in different directions at each depth from 25 m up to 60 m at all survey points, with some polygons showing interconnection of two fracture systems. Thirty-three percent of the polygons show principal fracture strike direction to be NE-SW, 30% show N-S direction, 22% show NW-SE direction while 15% show E-W direction. This trend agrees well with the geologically mapped surface fractures (figure 4) where 37% have orientation in the NE-SW, 22% have orientation in the N-S, 17% in the NW-SE while 12% are oriented in the NNE-SSW and 12% in E-W directions. This also shows that the primary groundwater flow direction (figure 5) of NE-SW in the study area is strongly influenced by fracture orientation.

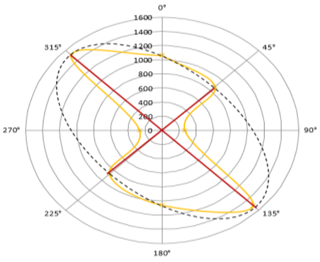
Station 1 **Station 2** **Station 3**



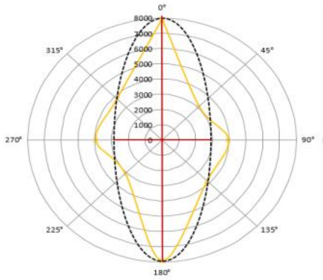
AB/2 = 2m



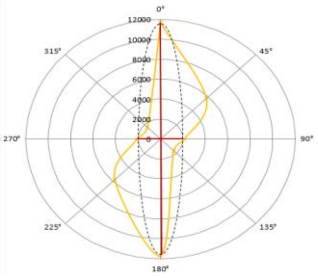
AB/2 = 2m



AB/2 = 2m

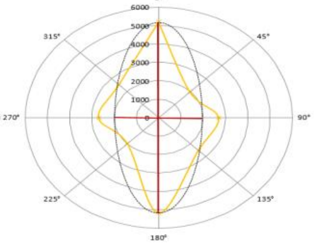


AB/2 = 5m

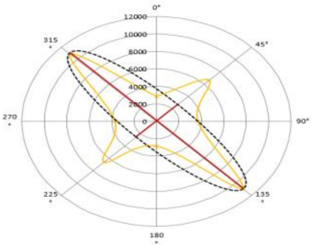


AB/2 =

5m

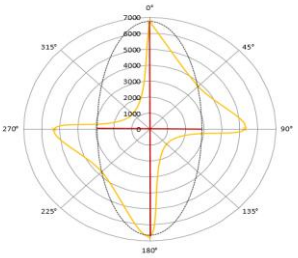


AB/2 = 5m

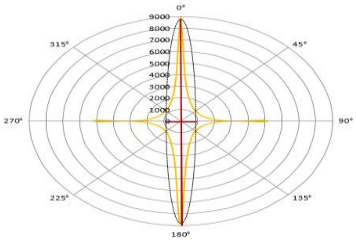


s

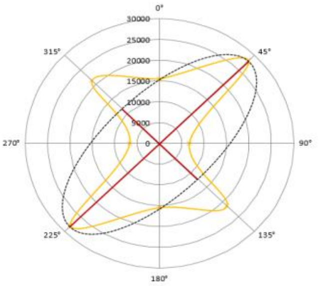
AB/2 = 10m



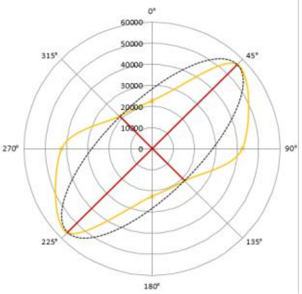
AB/2 = 10m



AB/2 = 10m



AB/2 = 20m



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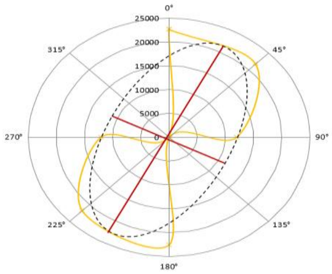
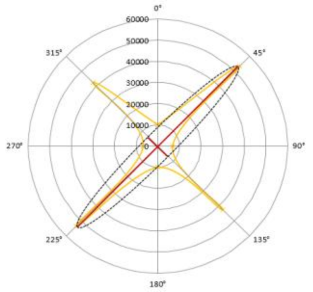
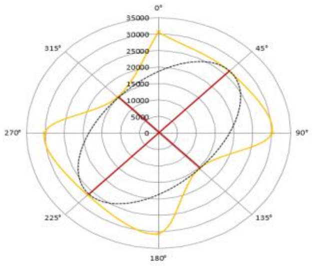


AB/2 = 20m



AB/2 = 25m



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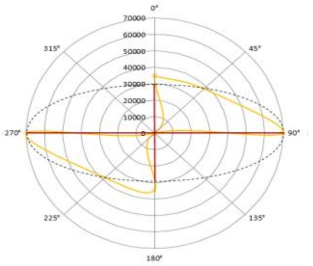
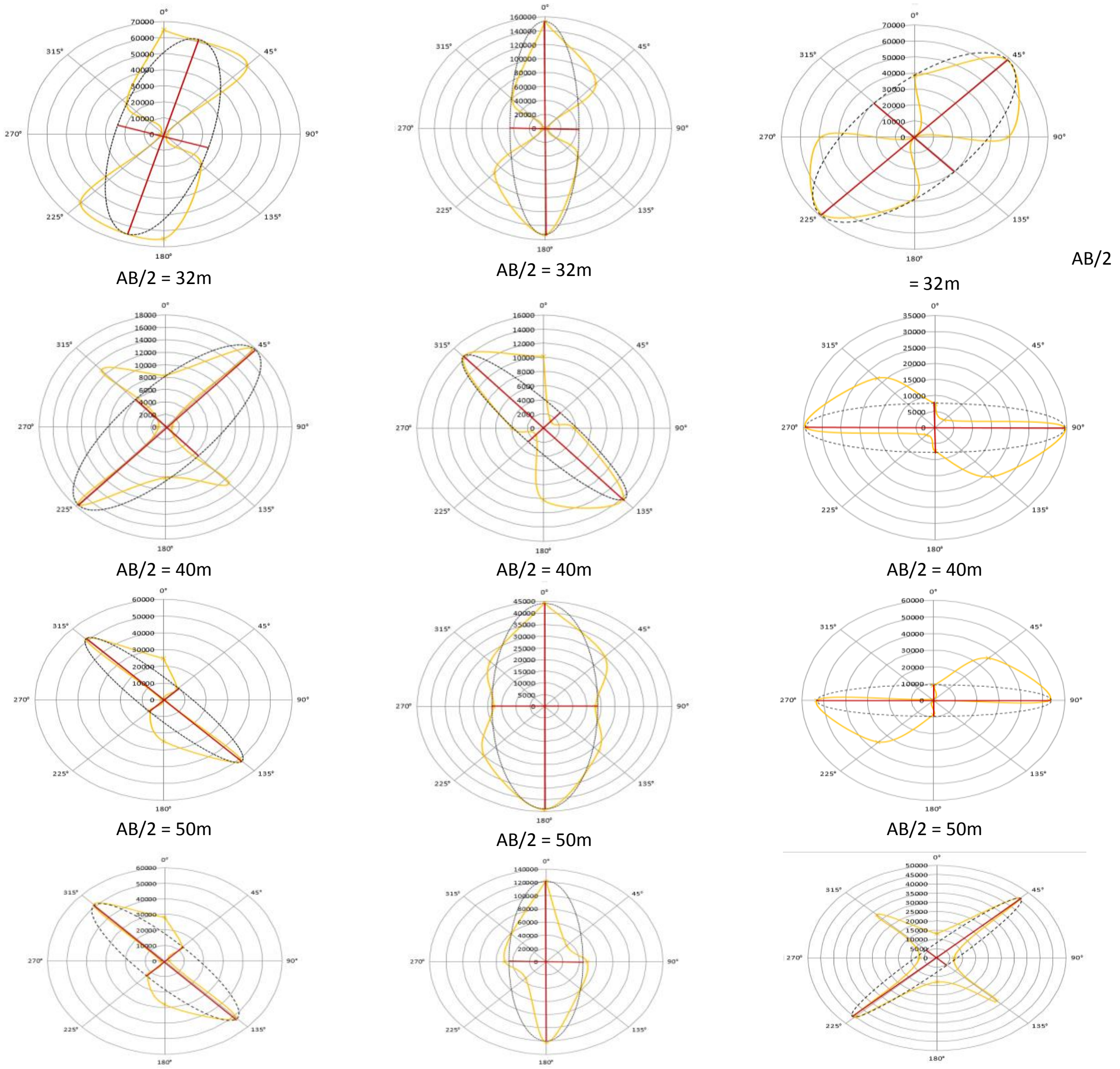


AB/2 = 25m



AB/2 = 32m
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AB/2 = 60m

Figure 8: Polar plots of electrical resistivity anisotropy in Gonin Gora

The coefficient of anisotropy (λ) calculated from the root of the ratio of major axis to minor axis of the best-fit ellipse to the anisotropy polygons in the study area varies between 1.34 and 3.00 with a mean value of 1.81 (table 2). From equation 1, an isotropic rock will have a coefficient of anisotropy of 1. The coefficient of anisotropy can be designated as the degree of rock fracturing (Olasehinde and Bayewu, 2011). Hence, a high value of coefficient of anisotropy will imply high degree of rock fracturing while a low value indicates less fracturing. From the values of the coefficient of anisotropy obtained in the area it is clear that the rocks in the study area are highly fractured with the rocks in station 3 being the most fractured.

Table 2: Summary of anisotropy characteristics of fractures in Gonin Gora

Electrode spacing (m)	Station 1		Station 2		Station 3	
	Inferred fracture strike direction	Coefficient of anisotropy (λ)	Inferred fracture strike direction	Coefficient of anisotropy	Inferred fracture strike direction	Coefficient of anisotropy (λ)
2	E-W	2.16	NW-SE	1.58	NW-SE	1.34
5	N-S	1.63	N-S	2.45	N-S	1.61
10	NW-SE	1.91	N-S	1.50	N-S	2.97
20	NE-SW	1.48	NE-SW	1.52	NE-SW	1.35
25	NE-SW	2.58	NE-SW	1.30	E-W	1.53
32	NE-SW	1.55	N-S	1.92	NE-SW	1.51
40	NE-SW	1.73	NW-SE	2.13	E-W	2.09
50	NW-SE	2.24	N-S	1.58	E-W	2.28
60	NW-SE	1.83	N-S	1.63	NE-SW	3.00

To qualitatively understand the behaviour of fractures with depth a plot of the values of coefficient of anisotropy (λ) against AB/2 for each survey station was made (figure 9). Anisotropy plots appear to be closing with depth at all the stations up till about 20 m, after which they tend to be opening with depth. However at station 1 the plot is closing beyond 50 m while at stations 2 and 3 the plots are opening beyond 50 m. The high values of the coefficient of anisotropy, even at depth in the study area is good for hydrogeological activities and portends good groundwater potential.

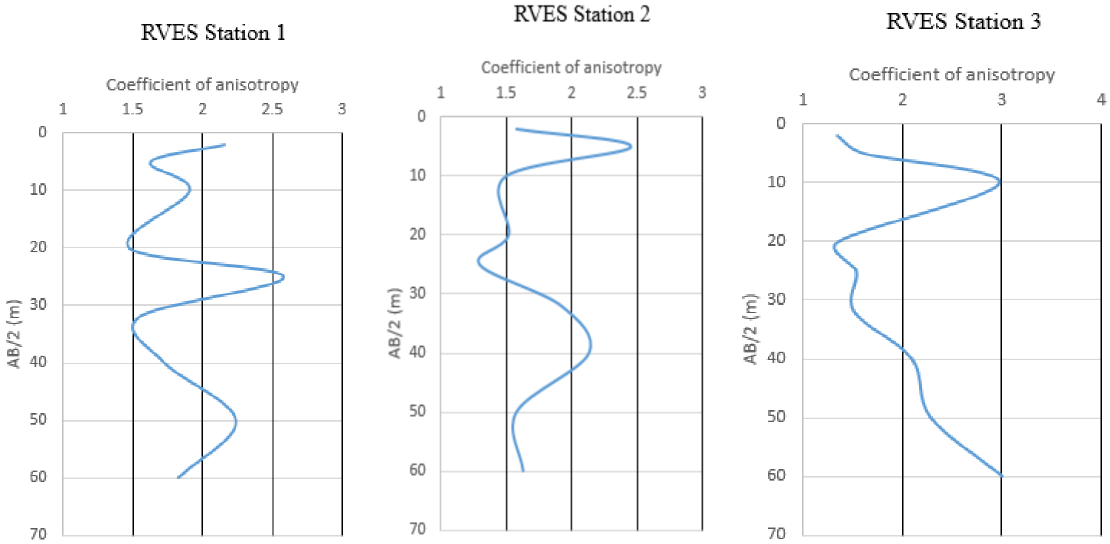

Figure 9: Variation of coefficient of anisotropy with depth in Gonin Gora

IV. Conclusion

This study has provided further insight into the hydrogeology of Gonin Gora which is another case of Basement hydrogeology. The weathered and fractured rocks provide groundwater for the open wells dug into the shallow aquifers in the study area. The principal fracture orientation in the area is NE-SW with other fracture systems oriented in N-S, NW-SE and E-W directions. Groundwater flow in the area is strongly influenced by the principal fracture orientation which makes groundwater to flow from southwest to northeast and contribute base flow to the rivers in the area. The plots of coefficient of anisotropy generally open with depth from about 30 m downwards, suggesting intense fracturing at depth. This indicates that boreholes drilled to beyond 30 m have good prospects of moderate to good yields, which is characteristic of Basement aquifers.

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