International Archive of Applied Sciences and Technology, Vol 1 [1] JUNE 2010: 45 -53

ISSN 0976- 4828
http:// www.soeagra.com

ORGINAL ARTICLE

Surface-outcrop characterization for fracture flow of groundwater: Case study of Abakaliki Basin, Ebonyi State, Nigeria

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ABSTRACT

Locating fracture zones in Abakaliki Basin by mapping their surface expressions was carried out to exploit their transimissivities for the development of water supply wells. Field observations and measurements show more orientations of fractures in the country NW and SE of the study area. Fracture porosities estimated from field measurement ranges between 0.2% and 2.2% while surface-area-to-pore-volume ration SAV related to permeability via Kozeny Carman relation of the fracture porous media varies between 14.38 and 288.75. Groundwater flow in the area is controlled by fracture. Groundwater flow direction as obtained by groundwater head contouring indicates dominant flow pattern in the SE orientation. The results of this study correlates perfectly with the tectonic framework (NW-SE) of the Abakaliki anticlinorioum.

INTRODUCTION

Fractures are the main groundwater flow path within the Abakaliki shale. Near-vertical fractures (joints and faults) cause flow to be oblique, instead of perpendicular, to the hydraulic gradient. Tectonic fracturing complicates groundwater flow patterns within the area. The hydraulic gradient, not the fractures, exerts the dominant control on the direction of groundwater flow. Fractures however have a direct influence on groundwater flow rate due to the generally lower frictional resistance to groundwater flow within fractures as against intergranular pores and to the fractures' role in lessening flow system tortuosity. The hydrologic impacts of a fracture zone can be profound. Locating fracture zones by mapping their surface expressions (fracture traces and lineaments) and exploiting their relatively high permeabilities for the development of water supply wells is not well known in the study area. In zones of relatively intense fracturing, hydraulic conductivities are often several orders of magnitude higher than in unfractured rocks, resulting in fracture-dominated flow (Schubert, 1980).

Most porosity and permeability in the Abakaliki basin is secondary. For example, bedrock aquifers usually include bedding-plane partings and near-vertical fractures, both secondary permeability features. Without such secondary features, the bedrock would likely not be a significant aquifer (Heath, 1989). However, the characteristics of the fractures (width, spacing, frequency, etc.) differ between, but may be consistent within, various stratigraphic units. Therefore, it is convenient to consider the stratigraphic units as the aquifers. The "typical" vertical profile on the plain consists of a shallow, unconfined (possibly including seasonally perched or semi-perched zones) system grading to a semi-confined system at intermediate depth.

Abakaliki basin is dominantly composed by single lithologic unit- shale, and can be characterized as either an aquifer or an aquitard over a relatively short lateral distance depending on conditions such as proximity to the shallow weathered zone, proximity to stream valleys, and magnitude of open joints (generally decreasing with depth). Shale units with low permeability, transmit large amounts of water, but transmit it vertically.

One important aspect of fracture flow is that the significance of any given fracture is scale dependent (major fractures on one scale can become minor fractures on another scale). Therefore, even for areas where fracture flow is dominant, sites can be modelled based on continuum assumptions if the fractures are relatively consistently spaced, are routinely interconnected, and the scale of the study area is large enough to treat as porous media.

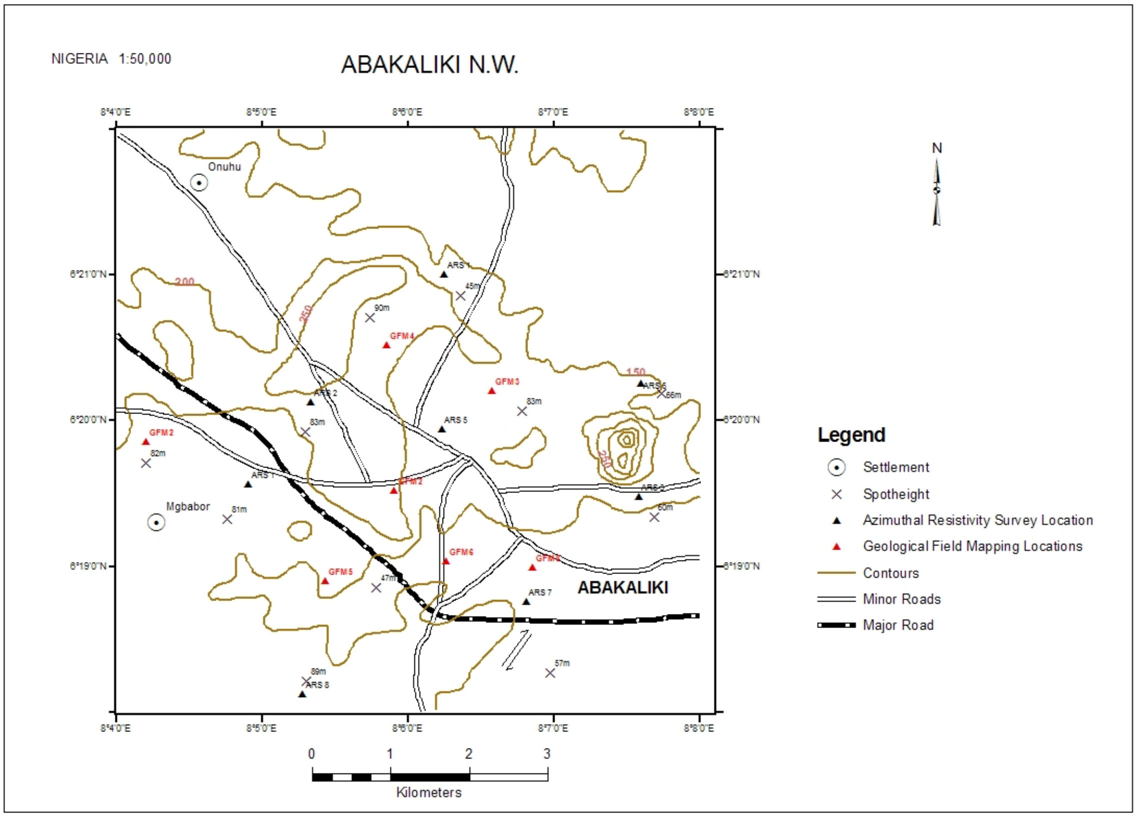

Figure 1: Map of Abakaliki showing the study area

Geology and Structure

The underlying rock in the area is the Abakaliki shale which lies within the Asu River Group of mid Albian age in the Southeastern Nigeria. The Abakaliki shale are poorly bedded, occasionally sandy, and consists of Splintery metamorphosed mudstones. Lenses of sandstone and sandy limestone are highly jointed and fractured.

The geologic history of Abakaliki basin, is characterized by compressional tectonic stresses. The associated stresses caused metamorphism and fracturing of older marine and volcanic rocks. Primary porosity is low due to geologic conditions. The low primary porosity suggests very poor groundwater transmission and storage capabilities; however, the development of secondary porosity by fracturing and faulting has lead to increase in the bulk permeability of the fractured shale. Secondary porosity is better developed at large-scale fractures observed on surface outcrops. Bedding is absent in most of the outcrops, and therefore, fracturing is not associated with bedding planes.

Aquifers of Abakaliki

Groundwater flow is largely controlled by three factors - the distribution and quantity of recharge to the flow system, surface topography, and the hydraulic conductivity of the material through which the groundwater flows. These factors may in turn be affected by a host of other elements - soils, climate, lithology, and geologic structure

An aquifer is a geologic formation capable of supplying water to wells economically. Water stored in aquifers is referred to as groundwater. 85% of the potable water used in Abakaliki comes from groundwater. Majority of these come from aquifers within Abakaliki.

Fractured shale aquifers store and transmit groundwater through an interconnected network of cracks known as fractures. Fractures in rock are caused in several ways, including folding of the rocks and faulting. The network of fractures in rock aquifers is often extremely complex. Fractures have different widths, which mean that water moves at very different rates in different fractures. However, in general, groundwater moves at a relatively slow velocity through the tortuous network of interconnected fractures in bedrock aquifers. Bedrock aquifers yield the most water where they are highly fractured, such as near faults and the center of folds.

Long et al. (1982) provided four criteria for analysing a fractured bedrock aquifer using an equivalent porous medium (EPM) approach.

These criteria are:

i) Sufficient fracture density,
ii) Constant fracture aperture rather than distributed aperture,
iii) The fracture orientations are distributed rather than constant,
iv) Large sample sizes are tested.

A description of the study area, in consideration of these criteria, is presented below. Our interpretation , with respect to the development of a conceptual model, is derived from geologic and structural descriptions of the bedrock geology, direct measurements made on outcrops of the exposed areas.

METHODOLOGY

Physical properties of fractures exposed on outcrops in the area were measured. Measurements of fracture orientation, aperture, trace length and spacing were made at eight outcrops. The spatial distribution of fracture density, aperture, and infilling characteristics of these sets is, in general, highly heterogeneous on the scale of the field measurement, and there is no systematic structure. The characteristics of these sets were heavily altered due to their exposure at the surface. Tectonic fractures were observed to be planar. Within the study area 8 locations were mapped. Some of these outcrops were found along road cut, river channel, and quarry site and in areas where the overburden has been scraped out. Most of the fractured zones observed in the field consisted of fractures in the vertical direction with few in sub-vertical direction.

The lengths, widths and strikes of the fractures are irregularly distributed. Appendix 1 shows the coordinates and the measured parameters such as fracture strike, fracture length, width, strike and dip of the bedding planes. Each of the locations is characterized by different fracture trends, which indicate that the deformation is as a result of force coming in different direction.

In some locations the fractures were measured on (pyroclastic) while others were measured on exposed shale outcrops. The fractures in locations: 1(ministry of works quarry), 4 (Amike Aba outcrop) and 5 (Azuiyiokwu river) trends in NE-SW direction while 2 (St. Banabas Church Ezza Umuezeokoha) , 6 (Nna street outcrop) and 8 (Abakaliki Girls High School) trends in the NW – SE direction.

RESULTS

In locations were the strike of the bed were measured figure 4, they strike in the same direction with the fracture (i.e. northwest - southeast). The dip amount of beds ranges from 20^0 to 34^0 except in location 8 where the shale has been strongly deform resulting to different geologic structures like folding and faulting. The dip amount measured in location 8 was vertical (i.e. 90^0).

The histogram in figure 2 shows the distribution of the facture strike with azimuth. The fracture strike and width are irregularly distributed. The polar plots in figures 3, 4 and 5 shows the orientation obtained from geologic field mapping by grouping locations with similar fracture trends (figures 3 and 4). Integration of figures 3 and 4 gave the overall fracture trends (figure 5) of all the locations where measurements were made.

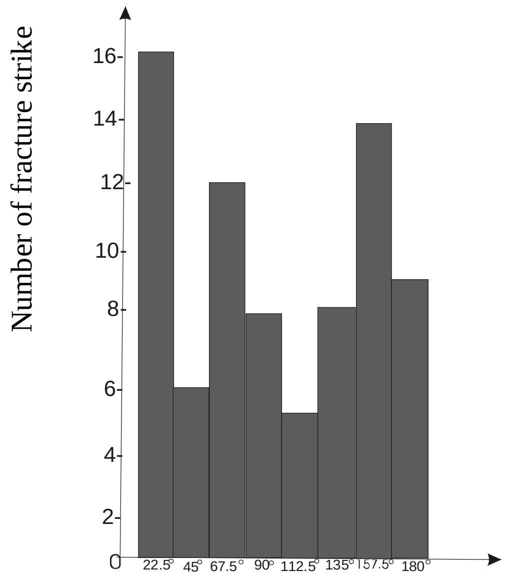

Figure 2: The distribution of fracture strike with azimuth.

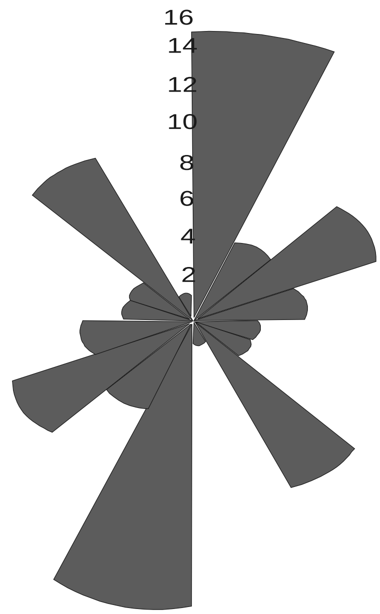

Figure 3: Polar plot of the fracture orientations obtained from geologic field mapping of outcrops at locations 1, 3, 4 and 5

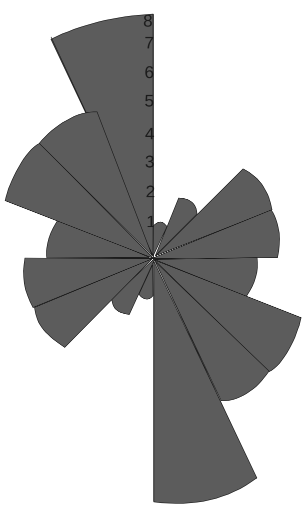

Figure 4: Polar of the fracture orientations obtained from geologic field mapping of outcrops at locations 2, 6, 7 and 8

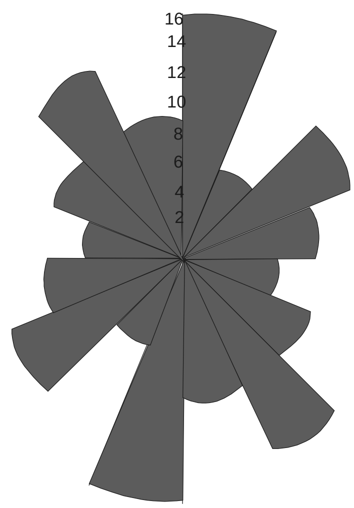

Figure 5: Composition polar plot of the fracture orientation obtained from geologic field mapping of the outcrops at all the eight locations in the study area.

Appendix 1 : Characteristic Fracture Parameters Obtain From Geological Field Mapping.

Azimuth	Fracture Trend	Li (lengths)	Wi Width (m)	Liwi	ϕ_f	**ϕ_f(%)**	**S_{AV}(μm)**
	20^0(NE-SW)	6.0	0.02	0.12			
	18^0(NE-SW)	6.0	0.004	0.024			
	5^0 (NE-SW)	6.2	0.04	0.248			
	18^0(NE-SW)	1.0	0.06	0.06			
	18^0(NE-SW)	2.5	0.12	0.3			
	20^0(NE-SW)	4.1	0.01	0.041			
	8^0(NE-SW)	0.4	0.02	0.008			
	12^0(NE-SW)	4.0	0.02	0.08			
0^0-22.5^0	10^0(NE-SW)	2.0	0.03	0.002	0.002	**0.02**	**164.5**
	0^0(N-S)	0.5	0.01	0.005			
	10^0(NE-SE)	0.4	0.01	0.004			
	20^0(NE-SE)	0.3	0.006	0.002			
	8^0(NE-SW)	0.84	0.004	0.003			
	10^0(NE-SW)	0.6	0.004	0.002			
	8^0(NE-SW)	0.8	0.003	0.002			
	20^0(NE-SW)	0.8	0.002	0.002			
	30^0(NE-SW)	5.0	0.02	0.10			
	40^0(NE-SW)	3.0	0.07	0.21			
	40^0(NE-SW)	0.8	0.02	0.016			
22.6^0-45^0	30^0(NE-SW)	3.0	0.03	0.090	0.004	**0.4**	**69.79**
	42^0(NE-SW)	8.0	0.02	0.16			
	40^0(NE-SW)	0.3	0.001	0.0003			
	50^0(NE-SW)	4.0	0.01	0.04			
	48^0(NE-SW)	6.5	0.01	0.065			
	64^0(NE-SW)	3.6	0.01	0.065			
	50^0(NE-SW)	1.0	0.01	0.01			
	48^0(NE-SW)	0.6	0.005	0.003			
	64^0(NE-SW)	0.58	0.004	0.002			
	60^0(NE-SW)	0.6	0.006	0.004			
45.0^0-67.5^0	50^0(NE-SW)	2.5	0.002	0.05	0.004	**0.4**	**56.22**
	50^0(NE-SW)	10.0	0.09	0.9			
	48^0(NE-SW)	0.9	0.001	0.001			
	50^0(NE-SW)	0.8	0.003	0.002			
	60^0(NE-SW)	1.3	0.002	0.003			
67.6^0-90^0	80^0(NE-SW)	0.43	0.004	0.002			
	78^0(NE-SW)	2.0	0.08	0.16			
	78^0(NE-SW)	2.0	0.08	0.16			
	74^0(NE-SW)	3.0	0.1	0.30			
67.6^{0-}90^0	74^0 (NE-SW)	3.0	0.1	0.30	0.016	**1.6**	**41.39**
	74^0(NE-SW)	0.5	0.005	0.003			
	80^0(NE-SW)	0.8	0.005	0.003			
	70^0(NE-SW)	0.8	0.004	0.003			
	80^0(NE-SW)	2.1	0.003	0.006			
	110^0(NW-SE)	4.0	0.02	0.08			
	98^0(NW-SE)	3.0	0.02	0.06			
	110^0(NW-SE)	0.3	0.01	0.003			
90.1^0-112.5^0	106^0(NW-SE)	0.11	0.002	0.0002	0.005	**0.5**	**107.08**
	98^0(NW-SE)	0.3	0.002	0.001			
Azimuth	Fracture Trend	Li (lengths)	Wi Width (m)	Liwi	ϕ_f	**ϕ_f(%)**	**S_{AV}(μm)**
	114^0(NW-SE)	5.0	0.300	1.500			
	120^0(NW-SE)	1.10	0.066	0.073			
	135^0(NW-SE)	0.5	0.003	0.002			
	130^0(NW-SE)	0.4	0.001	0.004			
112.6^0-135^0	120^0(NW-SE)	0.2	0.008	0.002	0.022	**2.2**	**15.06**
	120^0(NW-SE)	2.4	0.001	0.008			

	121^0(NW-SE)	2.4	0.001	0.002			
	130^0(NW-SE)	2.4	0.001	0.002			
	130^0(NW-SE)	0.8	0.003	0.002			
135.1^0-157.5^0	142^0(NW-SE)	6.0	0.40	2.400	0.020	**2.0**	**14.38**
	146^0(NW-SE)	0.9	0.01	0.009			
	140^0(NW-SE)	7.0	0.08	0.56			
	138^0(NW-SE)	1.0	0.064	0.064			
	140^0(NW-SE)	0.6	0.003	0.002			
	150^0(NW-SE)	1.0	0.01	0.01			
	142^0(NW-SE)	1.30	0.056	0.073			
	150^0(NW-SE)	2.0	0.006	0.012			
	150^0(NW-SE)	0.3	0.001	0.0003			
	138^0(NW-SE)	2.0	0.001	0.002			
	150^0(NW-SE)	1.1	0.004	0.004			
	150^0(NW-SE)	1.1	0.004	0.004			
	148^0(NW-SE)	1.2	0.04	0.48			
	138^0(NW-SE)	1.0	0.02	0.02			
	140^0(NW-SE)	0.8	0.009	0.007			
157.5^0-180^0	174^0(NW-SE)	0.5	0.01	0.005	0.002	**0.2**	**188.75**
	172^0(NW-SE)	3.0	0.01	0.03			
	160^0(NW-SE)	1.5	0.003	0.005			
	168^0(NW-SE)	1.10	0.01	0.011			
	160^0(NW-SE)	0.7	0.007	0.005			
	172^0(NW-SE)	0.6	0.004	0.002			
	178^0(NW-SE)	0.9	0.002	0.002			
	174^0(NW-SE)	0.14	0.001	0.0001			
	172^0(NW-SE)	0.8	0.005	0.004			

Calculation of Fracture Parameters from Geologic Mapping

The fracture porosity (ϕ_f) can be estimated from field measurements of fracture width **w** and length L along a scan line. (Hossain, 1992; Boadu, 2000) as

$$\phi_f = \frac{\sum_{i=i}^{m} li \times wi}{\sum lixh} \cdot \quad 1 \quad -5$$

where **m** is the number of fractures and **h** defines the span of maximum fracture length.
The fracture porosity was calculated; for each rotational angle (i.e. Azimuth).
These fracture porosity ϕ_f are secondary porosity that usually developed during tectonic fracturing of rocks and serves as measure of fluid storage potential of fractured rock mass.
Another important parameter characteristic of a fractured rock mass that is related to its hydraulic properties is the surface – area – to – pore - volume ratio S_{AV}. This parameter, also termed the specific area (inverse of a hydraulic radius), is related to the permeability of the fracture porous media via the kozeny – Carman relation (Wels and Smith, 1994).

$$S_{AV} = \frac{2\sum_{i=i}^{m} li}{\sum_{i=i}^{m} liwi} \quad 2 \quad 6$$

When l_i and w_i are, respectively, the length and width (aperture) of **ith** fracture within a fracture zone containing M fractures. The S_{AV} are estimated for locations where information about fracture apertures and lengths are available from geological mapping using equation 2. The specific surface area S_{AV} was estimated for the entire azimuth. By substitution of these value of ***m,h,l*** and ***w*** into equation(1),fracture porosity was calculated;

$0^0 - 22.5^0$

$\Sigma liwi = 0.443$

$h = 6.2$

$$\phi_f = \frac{0.443}{6.2 \times 36.4} = \frac{0.443}{225.68} = 0.002$$

2. $22.6^0 - 45.0^0$

$\Sigma liwi = 0.576$

$\Sigma li = 20.1$

$h = 9.0$

Also by substitution

$$\phi_f = \frac{0.576}{8.0 \times 20.1} = \frac{0.576}{160.8} = 0.004$$

3. $45.1^0 - 67.5^0$

$\Sigma liwi = 1.152$

$\Sigma li = 32.38$

$h = 10.0$

$$\phi_f = \frac{1.152}{32.38 \times 10.0} = \frac{1.152}{323.8} = 0.004$$

4. $67.6 - 90^0$

$\Sigma liwi = 0.475$

$\Sigma li = 9.83$

$h = 3$

$$\phi_f = \frac{0.475}{9.83 \times 3} = \frac{0.475}{29.49} = 0.016$$

5. $90.1^0 - 112.5$

$\Sigma liwi = 0.144$

$\Sigma li = 7.71$

$h = 4$

$$\phi_f = \frac{0.144}{7.71 \times 4} = \frac{0.144}{30.84} = 0.005$$

6. $112.6^0 - 135.0^0$

$\Sigma liwi = 1.589$

$\Sigma li = 14.2$

$h = 5$

$$\phi_f = \frac{1.589}{14.2 \times 5} = \frac{1.589}{71} = 0.022$$

7. $135.1^0 - 157.5^0$

$\Sigma liwi = 3.643$

$\Sigma li = 26.2$

$h = 7$

$$\phi_f = \frac{3.643}{26.2 \times 7} = \frac{3.643}{183.4} = 0.020$$

8. $157.6^0 - 180^0$

$\Sigma liwi = 0.064$

$\Sigma li = 9.24$

$h = 4$

$$\phi_f = \frac{0.064}{9.24 \times 3} = \frac{0.064}{27.72} = 0.002$$

1. $0^0 - 22.5^0$

$\Sigma li = 36.44$

$\Sigma liwi = 0.443$

by substitution with equ 6

$$S_{AV} = \frac{2 \times 36.44}{0.443} = \frac{72.88}{0.443} = 164.5$$

2. $22.6^0 - 45.0^0$

$\Sigma li = 20.1$

$\Sigma liwi = 0.576$

3. $45.1 - 67.5^0$

$\Sigma li = 32.38$

$\Sigma liwi = 1.152$

$$S_{AV} = \frac{2 \times 32.38}{1.152} = 56.22$$

4. $67.6^0 - 90.0^0$

$\Sigma li = 9.83$

$\Sigma liwi = 0.475$

$$S_{AV} = \frac{2 \times 9.83}{0.475} = 41.39$$

5. $90.1^0 - 112.5^0$

$\Sigma li = 7.71$

$\Sigma liwi = 0.144$

$$S_{AV} = \frac{2 \times 7.71}{0.144} = 107.08$$

6. $112.6^0 - 135.0^0$

$\Sigma li = 14.2$

$\Sigma liwi = 1.587$

$$S_{AV} = \frac{2 \times 14.2}{1.589} = 15.06$$

7. $135.1^0 - 157.5^0$

$\Sigma li = 26.2$

$\Sigma liwi = 3.643$

$$S_{AV} = \frac{2 \times 26.2}{3.643} = 14.38$$

8. $175.6^0 - 180^0$

$\Sigma li = 9.24$

$\Sigma liwi = 0.064$

$$S_{AV} = \frac{2 \times 9.24}{0.064} = 288.75$$

Hydraulic Head Distribution

The hydrogeologic complexity of fractured formations makes their characterization very difficult. The distribution of hydraulic head in fractured-rock aquifers can be difficult to measure because these aquifers commonly exhibit significant spatial and temporal variations in head as well as complex responses to recharge events (Muldoon, et, al., 2005). Detailed measurements of water levels in open wells in Abakaliki were carried out using global positioning system (GPS) and water level indicator with tape marked in 0.003m increments. Measurements were recorded to ±0.0005. Hydraulic heads were subsequently converted to meters to enable for GW contouring and visualization. The converted measured error is ±0.0015 m. Table shows the water head data obtained from wells in the study area in X(easting), Y(northing), Z(depth(m)) form. Figure is a contour map that shows the various directions of groundwater flow in the area. Velocities of the groundwater at various points in the area and the particle pathlines were obtained using an aquifer conceptual model:

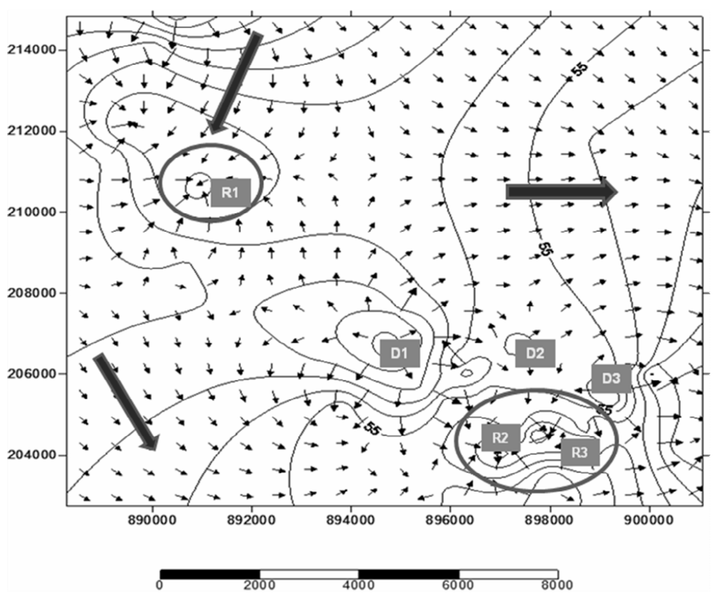

Figure 6: R1, R2, R3 indicate recharge zones; D1, D2, D3 indicate discharge zones while the red arrow show flow directions of groundwater.

The hydraulic gradient and anisotropy of the transmitting medium control the specific flow paths between recharge and discharge areas. In homogeneous, isotropic media groundwater flows perpendicular to equipotential lines. Anisotropy can result in flow which is oblique with respect to equipotential lines (Fetter, 1981).

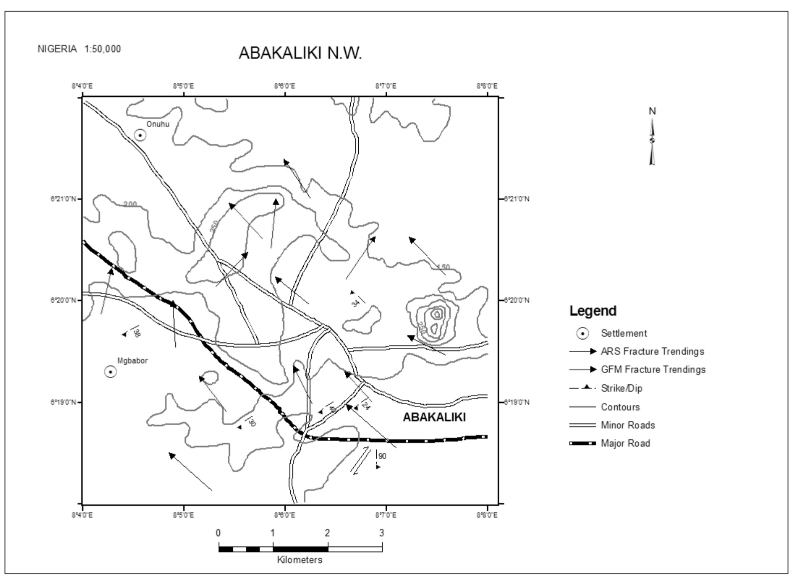

Figure 7: Structural trends inferred from outcrop field measurements

CONCLUSIONS

The following conclusions have been deduced from this study:

1. Fracture intensity and density is more in the country NW and SE(mainly in 135^0 orientation) of the study area, suggesting higher porosity and permeability hence, groundwater storage and transmission capability are better in those parts of the study area.
2. The trends of fractures correlate perfectly with the tectonic frame work of the area.

3. The axial trend of the Abakaliki anticlinoria is NW- SE. This conforms to the fracture trends predicted from ARS of previous study. These closely match the orientation of dominant fracture trend (112.5^0-157.5^0) from geologic field mapping in some outcrop around the study area
4. The values of the specific surface area ranges from 14.42 - 188.2 μs/cm.
5. Fractured rocks with relativity high fracture porosity and a relatively high coefficient of anisotropy are likely to be very permeable.
6. Net groundwater flow in the area is controlled by dominant fracture direction. This agrees well with the drainage pattern observed in the area.

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