International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 10 Issue 5 Series I || May 2021 || PP 07-34

Geological and PetrophysicalEvaluation of Afikpo Sandstone in Afikpo Sub-Basin, Southeastern Nigeria Using Integrated Approach

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Abstract
This research was carried out to evaluate the geological and petrophysical properties of Afikpo Sandstone within the Afikpo Sub-basin south-eastern Nigeria. Afikpo Sub-basin is believed to be the eastern extension of the Anambra Basin with similar Stratigraphic, sedimentological and structural correlations and proven hydrocarbon reserves in Nigeria. Bulk resistivities from the inversion of nine resistivity data with half electrode spread of 300m, grain sizes from sieve analysis of outcrop samples, and in-situ water resistivity of boreholes within the vicinities of the VES points wereused to calculate the parameters of the sandstone unit using Archie's rule and Kozeny–Carmen–Bear principles. The geophysical survey was integrated with a detailed geological mapping from which structural and stratigraphic information of the study area were modelled. Conventional techniques of acquiring petrophysical characteristics of rock units such as pumping tests are tedious, error prone and quite expensive especially in areas where wells are not available or widely spread. The basin fill was modelled using the elevations above sea level and geological information obtained during the geological mapping. The dominant rock types in the study area are sedimentary rocks such as sandstone, shales, siltstone and mudstone. There is also presence of dolerite intrusion in form of sills and pillow lava. The cumulative weight plot and structures suggest that they are river sands deposited by traction, suspension and saltation with tidal and tectonic influence. The sorting values of Afikpo Sandstone from the sieve analysis ranges from 0.50 to 1.17 which overlaps with the range of rivers and inland sand dunes. Porosities obtained range from 1.06 to 17.63 with an average of 6.05, hydraulic conductivity ranges from $6.5x10^3$ to $2.9x10^6$ m/day with an average of $8.2x10^5$m/day. The computed transmissivity values range from $5.2x10^5$ to $2.3x10^7$ m/day with an average of $6.8x10^7$m/day. Longitudinal unit conductance ranges from $7x10^{-5}$mS to 1.01mS with an average of $7.1x10^{-2}$mS, while the transverse unit resistance ranges from $8.2x10^3$Ohm-m^{2}to $1.6x10^6$Ohm-m^{2}with an average of $4x10^5$Ohm-m^2; this implies that on average the Afikpo Sandstone unit is suitable to serve as a potential reservoir/aquifer.

Keywords:*Afikpo sandstone, Unconventional, Petrophysical analysis, Kozeny-carmen-bear equation,*

Date of Submission: 07-05-2021 Date of Acceptance: 21-05-2021

I. INTRODUCTION

Conventional techniques of acquiring petrophysical characteristics of rock units such as pumping tests and laboratory analysis; are tedious, error prone, relative expensive and provide little information especially in areas where wells and outcrops are not available or widely spread. The application of near surface geophysical techniques such as resistivity method is useful and more convenient in estimating the reservoir/aquifer properties of rock unit. The geo-electrical property of a rock or material is influenced by its porosity, chemical composition of the rock type and volume of fluid present in its pores space, density and degree of compaction. Many literatures have reported empirical equations that relate electrical resistivity to the spatial distribution of petrophysical parameters such as porosity, hydraulic conductivity, transmissivity, depth and thickness of geo-electrical layers (Purvance and Andricevic, 2000; Lima and Niwas, 2000; Niwas and Celik, 2012). The conventional methods for these estimations include pumping tests, permeameter measurements and grain size analysis. Unfortunately, these methods are relatively expensive and require large volume of data which would only provide information only to a small section of the aquifer in the vicinity of the borehole (Soupios et al, 2007, Utom et al, 2012).

Interpolating aquifer properties between boreholes is often tedious with little or no data in which to base these extrapolations. Therefore, in areas of few pumping test data, surface resistivity method can provide useful information on subsurface conditions appropriately. The application of resistivity data in the estimation of aquifer can be a supplementary method applied in areas where information firmed test is insufficient or even unavailable (Macdonald el al 1999).

In the assessment of the hydrocarbon potentials or hydrogeological condition of rocks in a basin, four critical petroleum play element must be present for the former. These elements include the presence of a petroleum charge system (i.e. source rock and migration pathway), porous and permeable reservoir rocks which are in turn good aquifers, regional seal or cap rock forming a trap (Allen and Allen, 1990). The presence of the Nkporo Shale facies and the reported cases of the Nguzu-Edda hydrocarbon seepage are strong evidences of presence of hydrocarbon source. The puzzle however is the nature of the reservoir rocks and the trapping mechanism. Some exploration campaigns have been undertaken in the inland basins of Nigeria with the aim to expanding the national exploration and production base and to thereby add to the proven reserves asset. The inland basins of Nigeria comprise the Anambra Basin, the Lower, Middle and Upper Benue Trough, the southeastern sector of the Chad Basin (locally known as the Bornu Basin), the Mid-Niger (Bida) Basin and the SE Iullemeden Basin otherwise known as the Sokoto Basin

This study aims to evaluate the petrophysical properties of the Afikpo Sandstone which includes thickness, porosity, hydraulic conductivity, and transmissivity using an integration of Archie-Kozeny’s model and data derived from sieve analysis, surface resistivity measurements and laboratory resistively measurement from which a geo-electric and porosity section is modeled delineating various formational components.

II. GEOLOGICAL SETTINGS

The origin of many sedimentary basins in West Africa is associated with the breakup of the Gondwana supercontinent (Burke et al, 1971; Murat, 1972; Olade, 1975). This is believed to have been responsible for the creation of accommodation for the Benue Trough fill which started in the Jurassic. Other component basins formed at this time include the Gongola basin, the Yola rifts and Mamfe arms (Reyment, 1965;Petters et al, 1987). The ages of the basin fills generally decrease southwards from pre-Albian to Tertiary. Sediment thickness increase southwards towards the Niger Delta which is believed to have an average thickness of about 12km in the central parts of the Niger Delta (Doust and Omatsola, 1990). Sedimentation in the Lower Benue Trough commenced with the marine Albian Asu River Group, although some pyroclastics of Aptian – Early Albian ages have been sparingly reported (Benkhelil et al, 1989; Ojoh, 1992). The Asu River Group in the Lower Benue Trough comprises the shales, limestones and sandstone lenses of the Abakaliki Formation in the Abakaliki area and the Mfamosing Limestone in the Calabar Flank (Petters, 1980; Okoro and Igwe, 2014). The marine Cenomanian – Turonian Nkalagu Formation (black shales, limestones and siltsones) and the interfingering regressive sandstones of the Agala and Agbani Formations rest on the Asu River Group (Petters, 1980; Igwe, 2017; Okoro and Igwe, 2018). The formation and evolution of the Anambra basin started during the Santonian tectonic event (Okoro and Igwe, 2018). Before this time, the present day Anambra Basin was a platform with a thin succession of the older albian sediments. The orogenic event of the Santonian lead to the inversion of the basin which opened up the Anambra basin for deposition as sediments. This was facilitated by the compressional event which resulted to the uplift of the Abakaliki axis translating to the creation of the Anambra-Afikpo Syncline (Agagu et al, 1985). Sediments were derived from the uplands which are underlain by the basement complex of Nigeria. This provenance areas for sediments of the Anambra basin yielded dominantly texturally and mineralogically mature sediments from the crystalline basement areas including the North central granite suits, Southwest craton and the Oban massif. Post-deformational sedimentation in the Lower Benue Trough, therefore, constitutes the Anambra Basin. Sedimentation in the Anambra Basin thus commenced with the Campanian-Maastrichtian marine and paralic shales of the Enugu and Nkporo Formations, overlain by the coal measures of the Mamu Formation. The fluviodeltaic sandstones of the Ajali and Owelli Formations overlie the Mamu Formation and constitute its lateral equivalents in most places.

The Enugu and the Nkporo Shales represent the blackish marsh and fossiliferous pro-delta facies of the Late Campanian-Early Maastrichtian depositional cycle (Reijers and Nwajide, 1997; Odigi, 2012). Deposition of the sediments of the Nkporo/Enugu Formations reflects a funnel-shaped shallow marine setting that graded into channeled low-energy marshes. The coal-bearing Mamu Formation and the Ajali Sandstone accumulated during this epoch of overall regression of the Nkporo cycle (Okoro et al 2020). The Mamu Formation occurs as a narrow strip trending north–south from the Calabar Flank, swinging west around the Ankpa plateau and terminating at Idah near the River Niger. The Ajali Sandstone marks the height of the regression at a time when the coastline was still concave. The converging littoral drift cells governed the sedimentation and are reflected in the tidal sand waves which are characteristic for the Ajali Sandstone. The Nsukka Formation and the Imo Shale mark the onset of another transgression in the Anambra Basin during the Paleocene. The shales contain significant amount of organic matter and may be a potential source for the hydrocarbons in the northern part of the Niger Delta (Reijers and Nwajide, 1998).

The study area is a part of the Afikpo Sub-basin which lies at the eastern limb of the Abakaliki Anticlinorium, the western flank being in Anambra Basin. The study area which lies within the Afikpo Sub-basin rests on the highly deformed southern Benue Trough with an angular unconformity between them. The Santonian thermo-tectonic event resulted in the folding and uplifting of the Abakaliki axis which was flexurally inverted in a Northwest to Southeast trend depressions creating the Anambra and Afikpo Basins respectively (Figure 1).

Wright et al (1995) defined the Anambra Basin as the Upper Santonian - Maastrichtian depositional area located at the southern end of the Benue Trough, with which the Nkporo Group and the younger sediments accumulated and which extended towards the south-west as the Niger Delta Basin. The Anambra Basin fill is underlain by the Santonian unconformity linking the Southern Benue Trough to the Afikpo Synclinorium. The Santonian tectonic phase resulted in a lot of fracturing and folding in the Benue Trough giving rise to series of anticlines and synclines one of which is known as the Abakaliki Anticlinorium and Afikpo Synclinorium (Reyment 1965).

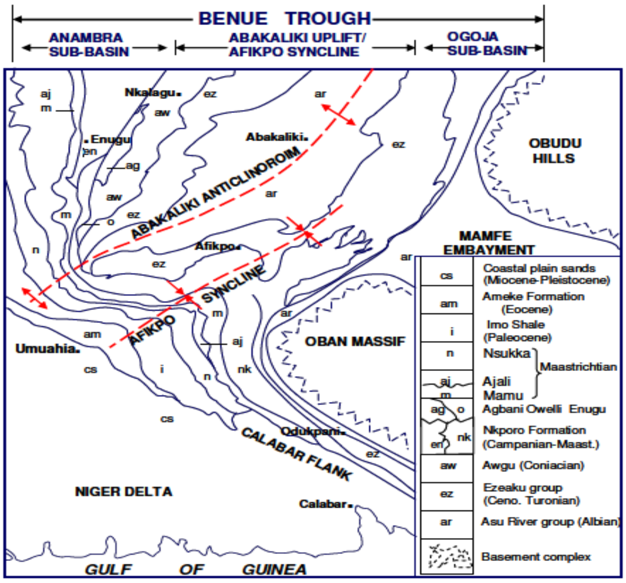


Figure 1: Regional Stratigraphic map of Southeast, Nigeria. (Modified after Akande et al, 2011)

The deformed and uplifted trough became positive elements to shed sediments to the new depressed platforms as sediments were also sourced from the Oban and Obudu Massif (Kogbe, 1989; Reyment, 1965).
The study area consist of two predominant and conformable geologic formations; the Campanian-Nkporo Group represented by the Afikpo formation.For this study, focus would be emphasized on the Afikpo formation (Table 1).

III. METHODS AND MATERIALS

3.1 Geological Field Mapping

The compass and traversing method using Global Positioning System (GPS) was adopted. Outcrops were located on the basemap and named serially. Careful observation and study of the outcrop using the fundamental bottom to top approach was used. The lithologies observed were described noting their color, textures, grain shape, grain size, sorting, cementing materials mineralogy and other properties at each location. This was achieved using physical/ visual observation and interpretation. Thickness of various beds in each location was taken and logged using the measuring tape orientation or attitude such as dips and strikes of beds, faults, fractures were taken using the clinometers and compass respectively. Descriptions of the nature and type of sedimentary structures exposed at the outcrop were noted and possible causes and implications were inferred. Rock samples were collected and properly numbered according to the location gotten for laboratory analysis. Equipment used during the geologic mapping include; Base map, compass clinometers, global positioning system (GPS), field note, masking tape, camera, geologic hammer, sample bags, markers and other writing materials.

The study area covers an area of 87,420m^2 (Fig. 2). This research was carried out in this part of the Afikpo Sub- basin because it consists of well exposed outcrops of the Afikpo Sandstone units which have been mapped and its field characteristics known. There are several already existing wells with lithology information providing a yard stick for the present study.

Table 1: The Stratigraphic Column of the South-Eastern Nigeria (Modified from Reyment, 1965).

<table>
<tr><th>GEOLOGIC AGE</th><th colspan="2">FORMATION</th><th>LITHOLOGY</th></tr>
<tr><td>Quaternary</td><td colspan="2" rowspan="4">Benin</td><td rowspan="4">Sandstone, Clay</td></tr>
<tr><td>Pliocene</td></tr>
<tr><td>Miocene</td></tr>
<tr><td>Oligocene</td></tr>
<tr><td rowspan="4">Eocene</td><td colspan="2">Ogwashi Asaba</td><td>Sandstone</td></tr>
<tr><td>Ibeku Formation</td><td rowspan="3">Ameki Group</td><td>Sandstone, Shale</td></tr>
<tr><td>Nanka Formation</td><td>Sandstone, Shale</td></tr>
<tr><td>Nsugbe Formation</td><td>Sandstone, Shale</td></tr>
<tr><td>Paleocene</td><td colspan="2">Imo Formation</td><td>Sandstone, Shale</td></tr>
<tr><td rowspan="3">Maastrichtian</td><td colspan="2">Nsukka Formation</td><td>Shale, Sandstone, Siltstone, Laterite</td></tr>
<tr><td colspan="2">Ajali Formation</td><td>Sandstone</td></tr>
<tr><td colspan="2">Mamu Formation</td><td>Shale, Sandstone, Siltstone, Coal</td></tr>
<tr><td rowspan="2">Campanian</td><td>Aminyi Edda Shale
Owutu Sandstone
Asaga Amangwu Shale|Enugu Shale</td><td rowspan="2">Nkporo Group</td><td>Shale, Sandstone, Mudstone</td></tr>
<tr><td>Afikpo|Owelli Sandstone</td><td>Sandstone, Mudstone</td></tr>
<tr><td>Santonian - Conciacian</td><td colspan="2">Agwu/Agbani Formation</td><td>Shale, Sandstone</td></tr>
<tr><td rowspan="3">Turonian</td><td>Makurdi Formation</td><td rowspan="3">Eze-Aku Group</td><td rowspan="3">Sandstone, Shale, Siltstone, Limestone, Mudstone</td></tr>
<tr><td>Amasiri Sandstone</td></tr>
<tr><td>Eze-Aku Shale</td></tr>
<tr><td>Cenomanian</td><td colspan="2">Odukpani Formation</td><td>Shale, Limestone</td></tr>
<tr><td rowspan="3">Albian</td><td>Mamfe Formation</td><td rowspan="3">Asu River Group</td><td>Sandstone</td></tr>
<tr><td>Abakaliki Formation</td><td>Shale, Limestone, Mudstone, Lenses of sandstone</td></tr>
<tr><td>Awe Formation</td><td>Sandstone, Shale</td></tr>
<tr><td>Pre-Cambrian</td><td colspan="3">Basement Complex</td></tr>
</table>

3.2 Petrophysical Evaluation

The petrophysical properties of Afikpo Sandstone were determined using data acquired from resistivity survey using vertical electrical sounding (VES), grain size information from sieve analysis and insitu resistivity of formation water from laboratory analysis which were fit into Archie-Kozeny fluid and ohm's current flow principles. VES was adopted to investigate and probe the subsurface using Schlumberger configuration (Figure 3).

Nine (9) VES data (Figure 2) was acquired with a maximum half electrode spacing of 300m. Grain sizes of representative samples of outcropping Afikpo sandstone around the vicinity of the VES points was calculated using sieve analysis. The resistivity of the formation water was calculated in the laboratory using chemical analysis.

The resistivity data acquired was processed using Interpex1XD software and was modelled using surfer 12. Equipments used during the resistivity survey include Geomative GD-20 model terrameter, wire reels, DC power source, GPS, electrodes, hammer, and cutlass; for the sieve analysis include a sieve set, an ASTM sieve shaker, brush and a sensitive electronic weighting balance.

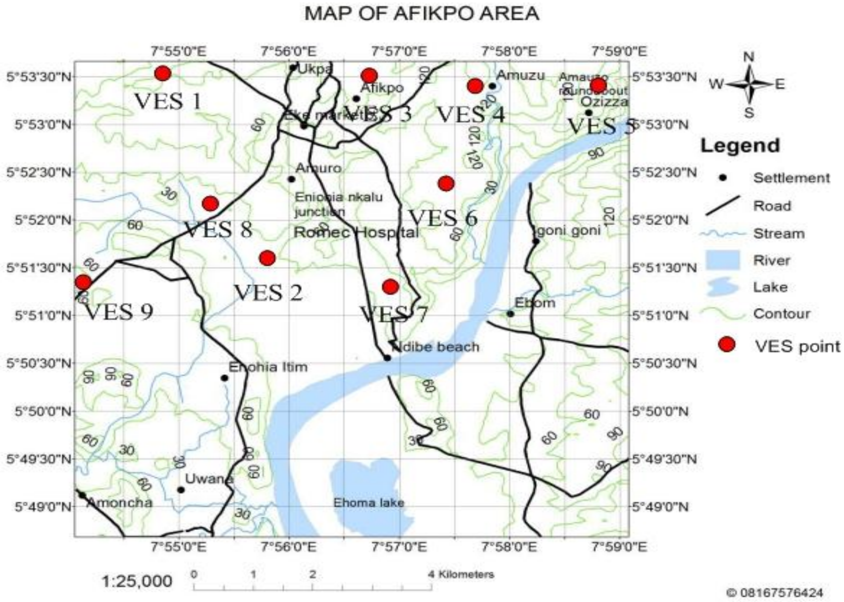


Figure 2: Base map with VES data points

In other to obtain quantitative information about the petrophysical properties of the Afikpo formation, a relationship between electrical resistivity and the volume of pore fluid was derived using the empirical formula given by Archie (1942). Artificially generated electric currents are introduced into the ground and the resulting potential difference was used to compute the bulk resistivities of the geo-electric layers.

Kearey et al, 2002 stated that certain minerals such as native metals and graphite conduct electricity via the passage of electrons, however, most rock forming minerals are insulators. In such medium electrical currents can only be carried through the rock unit by the passage of ions in the pore fluid.

The theory of surface resistivity method is built on a relationship between voltage and current through a conductor between two points is directly proportional to the voltage across the two points (Millikan and Bishop, 1917), introducing the constant (Resistance). The equation below is derived

$$\boldsymbol{V = I.R} \text{..................1.1}$$

Where;
V is the potential difference between two points (Volts)
R is the resistance (Ohms)
I is the current flowing through the material (Ampere).
The resistivity of a material is defined as the resistance in ohms between the opposite faces of a unit cube of the material, for a conducting cylinder of resistance, R, length, L, and cross-sectional, A, the resistivity, **ρ,** is given by Lowrie, 2007 (equation 1.2).

$$\boldsymbol{\rho = \frac{R.A}{L}} \text{..................1.2}$$

Resistivity was measured using the Geomative GD-20 terrameter which also computed the apparent resistivity, $\boldsymbol{\rho_a}$,using equation 1.3.

$$\boldsymbol{\rho_a = K\,.\,R} \text{........1.3}$$

where
K= Geometric factor.
The geometric factor is dependent on the electrode array (Reynolds, 2000). Lowrie 2007 illustrated the derivation of geometric factor for Schlumberger array. The current and potential pairs of electrodes have a common midpoint but the mid-distance between these electrodes differs. If the distance between the current and potentials are L and a respectively, the geometric factor is expressed as

$$\boldsymbol{K = 2\pi}\left[\left(\frac{2}{L-a}-\frac{2}{L+a}\right)-\left(\frac{2}{L+a}-\frac{2}{L-a}\right)\right]^{-1}$$

$$\boldsymbol{K = \frac{\pi}{4}\left(\frac{L^2-a^2}{a}\right)} \text{...........1.4}$$

considering the combined potential difference at MN and AB.

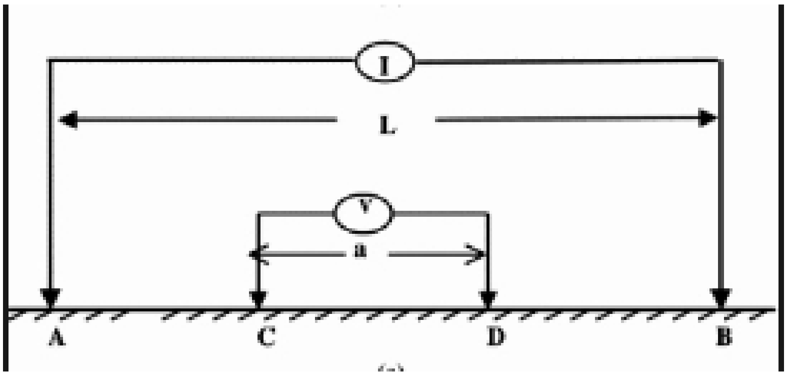


Figure 3: Schlumberger array

Substituting equation 1.4 into equation 1.3 and expanding it, we have apparent resistivity as

$$K = \frac{\pi}{4}\left(\frac{V}{I}\right)\left(\frac{L^2-a^2}{a}\right) \text{..........1.5}$$

Porosity was estimated using the empirical relationship from Archhie's (1942,1950) equation for electrical resistivity (ρ).

$$\rho = a\rho_w \emptyset^{-m} \quad \text{..........1.6}$$

From which when rearranged, porosity is given as

$$\emptyset = e^{\frac{1}{m}In(a)+\frac{1}{m}In\frac{1}{F_a}} \text{..........(1.7)}$$

Where F_a, is the formation factor which is the ratio of the bulk resistivity of the pore fluid (equation 1.4)

$$F_a = \frac{\rho}{\rho_w} \text{.........(1.8)}$$

Where

ρ- Bulk resistivity (ohm-m)

a - Electrical tortuosity parameter (-);See table 2 and 3for values

ρ_w- Resistivity of pore fluid (ohm-m)

$\emptyset$- Porosity of the rock unit (-)

M - Cementation factor (-); See table 2 and 3for values.

Table 2: Archie law coefficients (Keller, 1988)

Types of grains or rocks	Coefficient m	Coefficient a
Unconsolidated sand	1.37	0.88
Moderately cemented sedimentary rocks (sandstone and limestone)	1.72	0.62
Strongly cemented sedimentary rocks	1.95	0.62
Very porous volcanic rocks	1.44	3.50
Crystalline and metamorphic rocks	1.58	1.40

Table 3: Values of cementation factor (Doveton, 1988)

Formation type	Cementation value
Unconsolidated sand	1.3
Very slightly cemented sandstone	1.4-1.5
Slightly cemented sandstone	1.5-1.7
Moderately cemented sandstone	1.8-1.9
Highly cemented sandstone	2.0-2.2

The bulk resistivity of the rock unit was estimated from surface resistivity measurements. The resistivity of pore fluid was estimated using laboratory chemical analysis.

Domenico and Schwartz, 1990 illustrated the Kozeny-Carman- Bear's equation (equation 1.8) given by Kozeny, 1953 from which hydraulic conductivity K, estimation can be achieved.

$$K = \frac{\delta_w g}{\mu} \cdot \frac{d^2}{180} \cdot \frac{\emptyset^3}{(1-\emptyset)^2} \text{..............(1.8)}$$

Where g- acceleration due to gravity (9.81 m/s^2)

d - Grain size (m)

δ_w - Water density (1000 kg/m^3)

μ - Water dynamic viscosity (0.0014 kg/ ms)(Niwas and Celik, 2012)

Grain size (d) can be estimated from sieve analysis using statistical equation for mean (equation 1.9) (Table 4).

$$Mean = \frac{\emptyset 16+\emptyset 50+\emptyset 84}{3} \text{..............1.9}$$

Rock thickness (in this case, geo-electric layer thickness) was estimated from the inversion of the resistivity data.Transmissivity, T, is a function of the rock thickness and the hydraulic conductivity (eqn1.10). It defines the permeability of the formation.

$$\boldsymbol{T = K.b}\ldots\ldots\ldots\ldots\ldots 1.10$$

Niwas and Singhal(1981, 1985) derived two analytical equations for computing transmissivity from Longitudinal unit resistance, TR, using ohm's law of current flow and Darcy's law for horizontal fluid flow (equation 1.11 and 1.12). These define the Zarrouk parameters.

$$T = \alpha . S\ ;\ \alpha = k.\rho\ldots\ldots 1.11$$

and

$$T = \beta T_R\ ;\ \beta = k/\rho\ldots\ldots 1.12$$

Where

T_R- Transverse unit resistance ()(equation 1.13)

S- Longitudinal unit conductance () (equationn 1.14)

b- Rock thickness (m)

α, β- Constant of proportionality (-)

$$T_R = R\ .b\ \ldots\ldots\ldots\ldots 1.13$$

$$S = b/R\ldots\ldots\ldots\ldots 1.14$$

3.3 Sieve Analysis

Equipment used during the sieve analysis includes a sieve set, an ASTM sieve shaker, brush and s sensitive electronic weighting balance.The samples were labeled corresponding to the location they were gotten. The samples were disintegrated and sun dried. 50 grams of the samples was weighted using the sensitive electronic weighing balances and was sieved. After the shaking was completed, each sieve was carefully poured onto a sheet of paper and the mesh gently brushed from the bottom ensuring that no particle was lost. Each fraction gotten from each sieve was weighed separately and recorded on the data sheet. The experimental error was calculated which accounted for the sieve loss. The mass retained and cumulative % weight retained for each sieve was calculated and corrected. Percent cumulative weight was plotted against phi size (ø). Statistical parameters such as mean, standard derivation, skewness, and kurtosis were calculated using the following formula in the table below. The results and graphs of the sieve analysis are presented in the appendix 1-14

Table 4: Formula for Statistical parameters (Folk and Ward, 1957)

STATISTICAL PARAMETER	FORMULA
MEAN	$\pi = \frac{\text{Ø}16 + \text{Ø}50 + \text{Ø}84}{3}$
STANDARD DEVIATION	$S.D = \frac{\text{Ø}84 - \text{Ø}16}{4} + \frac{\text{Ø}95 - \text{Ø}5}{6.6}$
SKEWNESS	$SK = \frac{\text{Ø}84 + \text{Ø}16 - 2\text{Ø}50}{2(\text{Ø}84 - \text{Ø}16)} + \frac{\text{Ø}95 + \text{Ø}5 - 2\text{Ø}50}{2(\text{Ø}95 - \text{Ø}5)}$
KURTOSIS	$KG = \frac{\text{Ø}95 - \text{Ø}5}{2.44(\text{Ø}75 - \text{Ø}25)}$

IV. RESULTS AND DISCUSSION

4.1 Local Stratigraphy

The study area has two predominant and conformable geologic formations: The Campanian Nkporo Group represented by the Afikpo Formation and the Early Maastrichtian Mamu Formation (Table 5). Stratigraphically, the Afikpo Formation overlies the Ezeaku Shale of the Southern Benue Trough unconformable with an angular unconformity between the two. This is observed just before stepping into the study area at the base of the Macgregor hill. The Afikpo Formation is overlain by The Mamu Formation (Table 5), which occurs at the southwestern area around the Unwana area (Figure 4).

Table 5: Stratigraphic Succession of the study area

AGE	FORMATION	LITHOFACIES
EARLY MAASTRICHTIAN	MAMU FORMATION	Heterolytic unit of sandstones, siltstones, mudstones, shales, and lignitic bands
CAMPANIAN	AFIKPO FORMATION	Sandstones, mudstones, shales, siltstones, and ironstones.

The term Afikpo Formation (Table 5) is used to account for the heterogeneous (non-monolithic) nature of the formation as it consists of sandstone, shale, siltstone, and mudstone members. The presence of Dolerite intrusion trending in a NW-SE direction which occurs at the Northwestern part of the study area was traced. This study focuses on the Afikpo Formation.

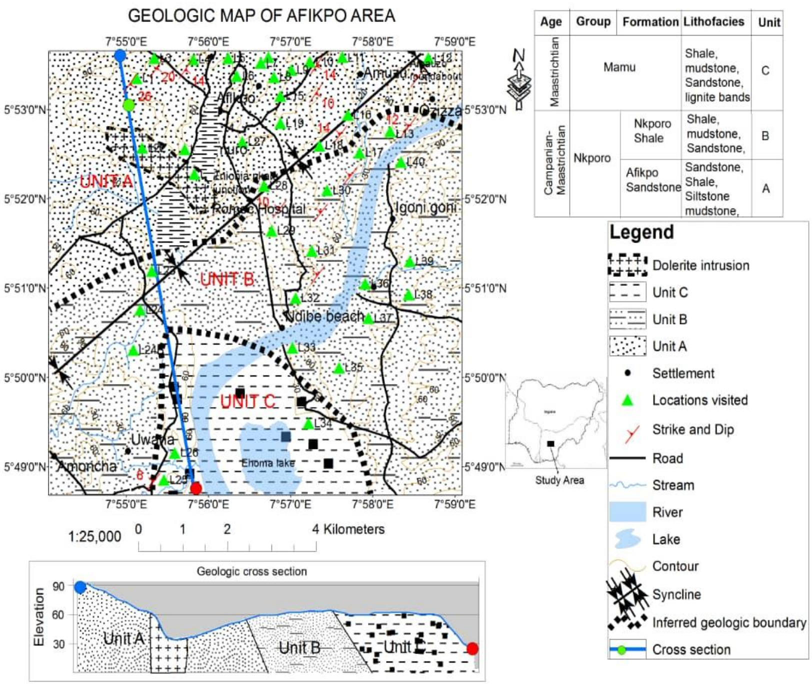


Figure 4: Geologic map with location visited

4.2 Description of Lithologic Units

4.2.1 Unit A (highly bioturbatedcoarsing upward sandstone and shale unit)

This is the oldest unit in the study area. It overlies the Ezeaku Formation unconformably. It occupies the northern part of the study area.

Figure 4: Panoramic view of highly bioturbed sandstone unit as seen at Macgregor block industry (Hammer for scale = 30cm).

It consists predominantly of well exposed sandstones with few exposures of dark grey shales. Field relationship shows that the shale overlies the sandstone unit as seen at the hill opposite Egesco Hotel, Afikpo just before ascending towards AkanuIbiamgirls college, Mgbom. The sandstone was deposited in a coarsing upwards sequence from fine-medium-coarse grain with scattered pebbles and presence of conglomeritic bands interbeds (Figure 5).

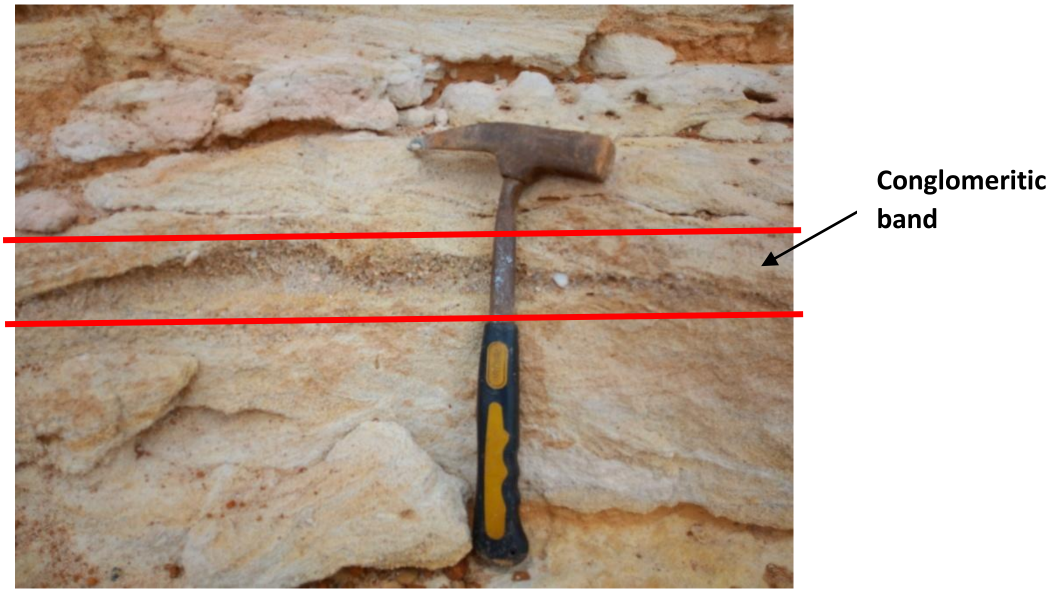


Figure 5: Conglomeritic band as seen in Amaozara sand mine.

The sandstones are highly bioturbated with presence of vertical and horizontal burrows of Orphiomorphia and skolithosichnofossils (Figure 4), the intensity of bioturbation reduces upward the sequence as the grain size increases. The sandstone are texturally immature but are mineralogically mature, this is because they are composed of about 60% quartz grains examined by physical observation. They are calcite cemented but some have iron-oxide as their cementing material due to secondary chemical alteration process. This chemical alteration leads to the ferrugenization of the sandstone (Figure 6). This process is aided by the high abundance of iron mineral in the presence of water and oxygen. The sandstones were deposited in a number of environments leading to the occurrence of varieties of facies.

Figure 6: Ferruginized sandstone as seen around Ukpa area

Facies A:Poorly sorted, medium to very coarse grained sandstones with scattered pebbles (Figure 8), bioturbated with calcite cementing material and sub angular quarts grains. This was deposited in shallow marine moderate energy environment as evident by the high crest symmetric wave ripple marks presents (Figure 7)

Facies B:Poorly sorted, bioturbated, fine – medium grained sandstone with calcite cementing material and sub angular quartz grains. This was deposited in a shallow marine low energy environment as evident by the low crest asymmetric current ripple marks and lamination present (Figure 9).

Facies C:Moderately sorted, fine grained sandstone bioturbated and milkfish –purplish with calcite cement material and sub-rounded quartz grains. It is laminated and thinly bedded (Figure 10). It is deposited in a shallow marine, pro-deltaic setting with low energy as evident by the grain size and lamination.

These facies A, B, and C are well observed at an outcrop just before Ebonyi Hotel, in front of Macgregor, behind a mechanic workshop and at a road cut along Ozizza road. The facies grade upwards in a coarsing up fashion from C to B to A (Figure 11, 12 and 13; Table 6, 7, and 8).

Figure 7: Ripple marks as seen at Ebonyi hotel, Afikpo.

Figure 8: Scattered pebbles as seen along Ozizza road.

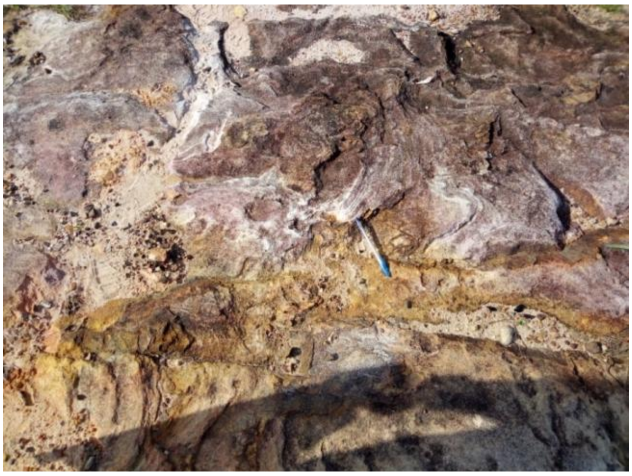


Figure 9: Horizontal lamination as seen in Ebonyi hotel area, Afikpo.

Figure 10: Thinly bedded sandstone unit with horizontal lamination

Figure. 11: Coarsing up sandstone unit as seen at the mechanic work shop about 200m from Macgregor block industry

Table 6: Litholog of outcrop at mechanic work shop about 200m from Macgregor block industry.

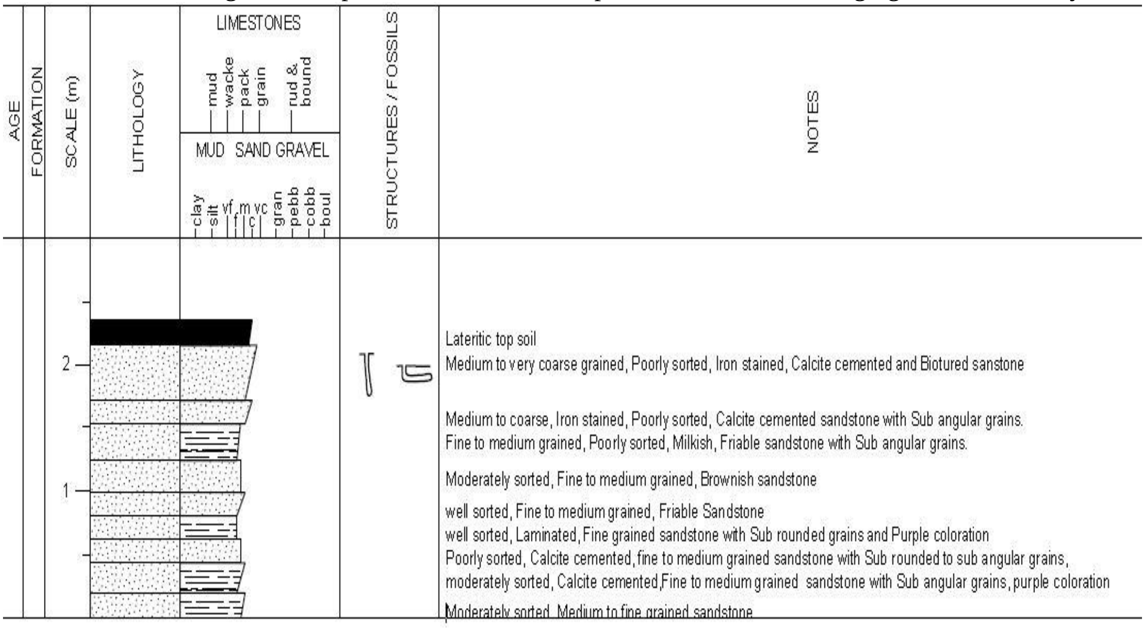
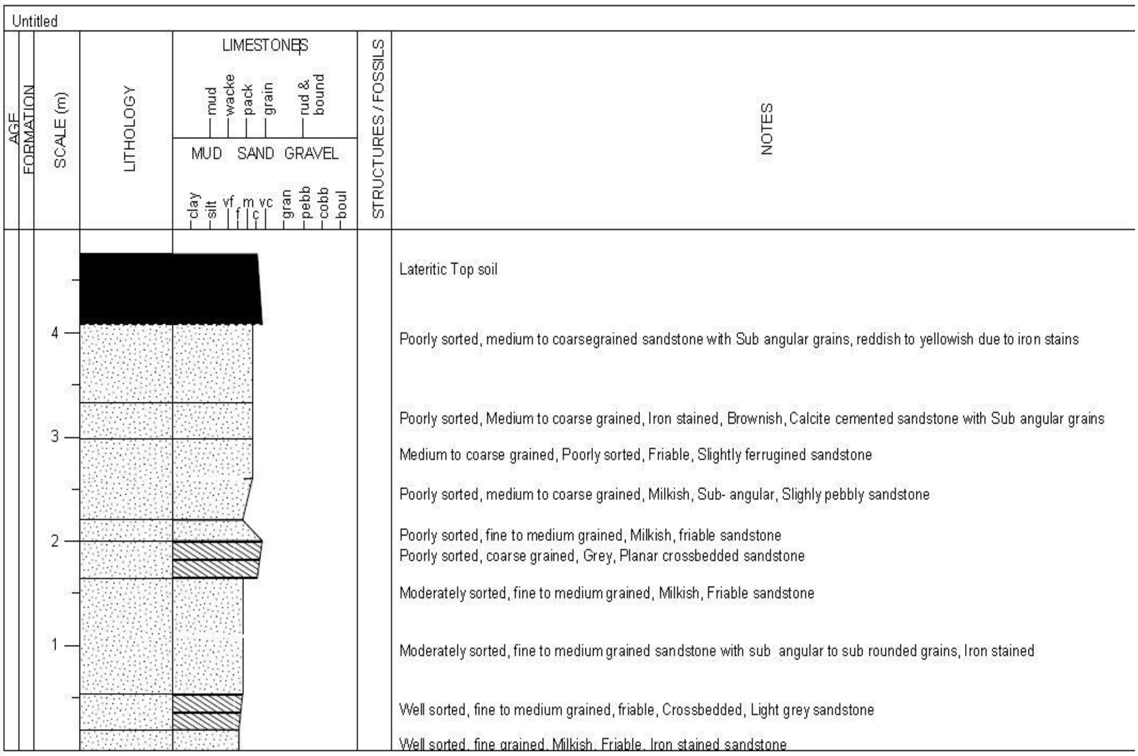


Fig. 12: Coarsing up sandstone unit as seen at road cut along Ozizza road.

Table 7: Litholog of outcrop at road cut along Ozizza road

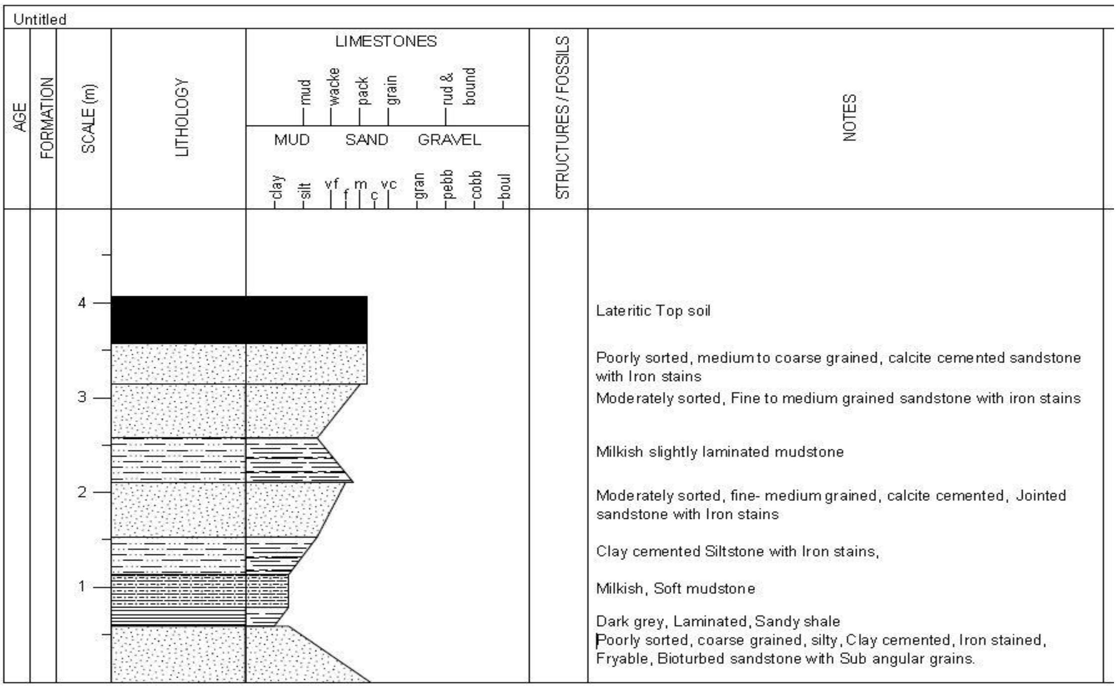


The fine grained sandstone appears to be laminated but as their grain size increase, they become cross bedded (Figure 14).

There is a transition from the sandstone units to shale by the occurrence of siltstone and mudstone at the base of facies C as seen in location 15 and location 7 which are heterolytic units consisting of top occurrence of sandstones to siltstones to mudstones to basal occurrence of sandy shales (Figure 13).

Fig. 13: Hetreolytic unit as seen in location 7 along Mata road.

Table 8: Litholog of the outcrop along Mata road.



The unit is highly fractured with general trend of NE-SW and very few NW-SE. Some fractures have iron oxide fillings. Fractures and joints were observed in all locations of the study area.

The shale has observed in location 7 (along Ozizza road) and location 14 (opposite Methodist church OgwugwuMgbom) are dark grey (Fig. 21), unconsolidated, laminated, friable, and fissile. The shales are easily weathered and covered by top soil. They contain gypsum needles along the laminar of the shales.

Figure 14: Crossbedded medium to very coarse sandstone unit

Figure 15: Dark shales as seen in location 14 (opposite Methodist church OgwugwuMgbom)

4.2.2 Unit B (highly ferrugenized, medium-coarse grained, crossbedded sandstone and shale unit)

This unit overlies unit A. it occupies the central part of the study area. Unit B outcrops in EnohiaNkalu, EnohiaItim, Ndibe area, Igonigoni, Eboma area, e.t.c. The unit consists of sandstone and poorly exposed shales at the valley areas. The unit consists of poorly sorted coarsing upward sandstone sequence from fine to medium sands to conglomeritic beds as observed in location 30c and 32 around EnohiaNkanu community and along Ndibe beach road (Figure 16, 21, and 22).

Figure 16: Conglomeritic facies and bioturbed basal unit as bioturbed in EnohiaNkanu community.

This unit is highly ferruginized (Figure 17 and 18). The sandstone has been chemically altered into ironstones. This alteration has affected their cementing material becoming iron-oxide cemented this increasing the hardness and consolidation of the sand stones.

Figure 17: Highly ferruginized sandstone unit

The fresh parts of the sandstones are milkish and calcite cemented (Figure 16 and 20) but the altered parts are reddish – brownish and have iron oxide as their cementing material (Figure 18). The basal beds are slightly bioturbated with the presence of horizontal and vertical burrows of Ophiomophiaichnofacies (Figure 16). The unit is crossbedded(Figure 18) with sub-angular grains. It is highly fractured (Figure19 and 20) with general trend of NE-SW with a few joints trending NW-SE. There is presence of iron concentrations.

Figure 18: Ferruginizedcrossbedded sandstone unit

Figure 19: Panoramic view of location 30 at EnohiaNkanu

Figure 20: Highly fractured sandstone unit with joint sets seen at Ebom.

Figure 21: Bioturbated sandstone outcrop in EnohiaNkalu Community.

Table 9: Litholog of outcrop in EnohiaNkalu Community.

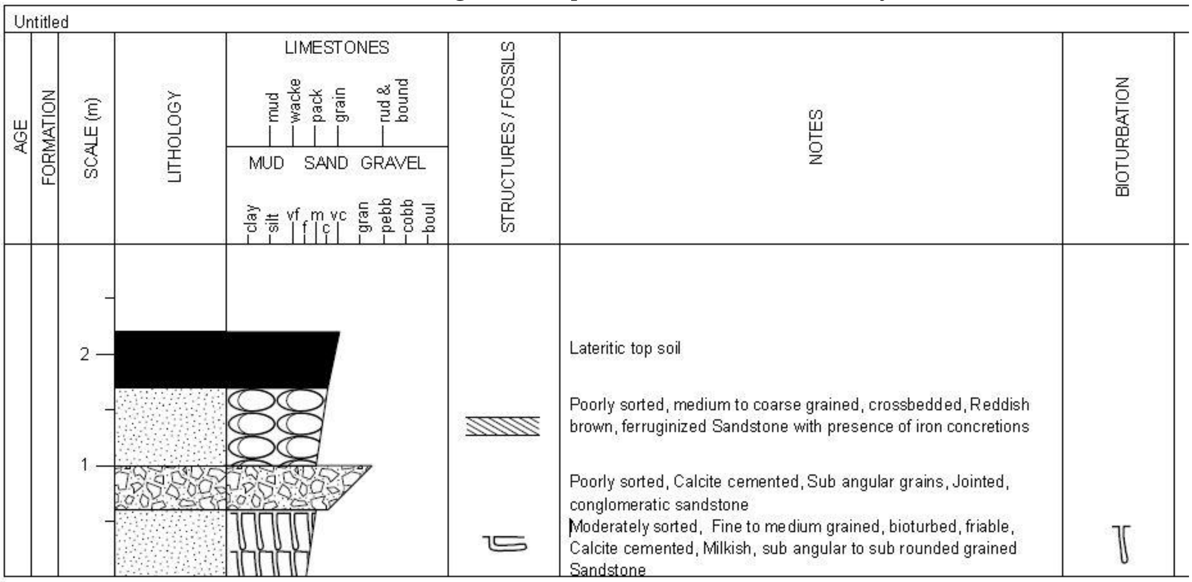
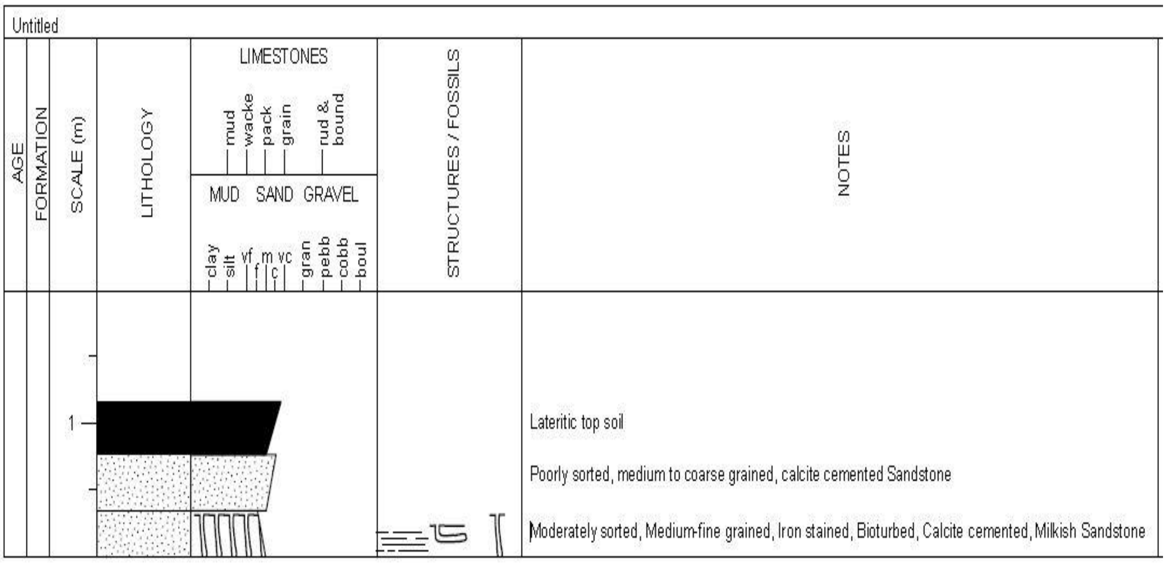


Figure 22: Outcrop in front of Ndibe beach hotel.

Table 10: Litholog of outcrop in front of Ndibe beach hotel



4.3 Sedimentary Structures

4.3.1 Ripple marks

Ripple marks come in two forms, symmetric or wave produced ripples and asymmetric or current produced ripples. The wave produced ripples a symmetric profile because of the bi-directional motion of waves while the current produced ripple marks have an asymmetric profile. Both asymmetric and symmetric ripple marks present in the study area (Figure 25). They can be observed beside around the Ebonyi Hotel, Afikpo. The asymmetric ripple mark indicates a highly unidirectional ripple how energy current dominated environment with bidirectional wave oscillations which is highly agitated with weak currents.

Figure 25: High crest ripple marks as seen in Ebonyi Hotel

4.3.2 Bedding

This refers to the layering that occurs in sedimentary rocks as a result of different depositional episodes. Each layer is referred to as a bed. Bedding planes are clearly exposed in most outcrops in the study area especially the sandstone outcrops (Figure 26).

Figure 26: Well bedded sandstone unit seen at mechanic shop about 200m from Ebonyi hotel

4.3.3 Laminations

Laminations are bed forms with thickness less than 1cm. These deposits are typically formed by fire grained sediments such as silts, clays and shales. Laminations are observed in unit A beside Ebonyi Hotel (Figure 26) and along Mata road (Figure 27).

4.3.4 Crossbeddings

Crossbeds are group of inclined layers which are known as cross stratification. They intercept the bedding plane at the top and base. They form during deposition on an inclined surface of bedforms such as ripples or dunes. Crossbeds as seen in the study area occurs among the medium – coarse sand stones (Figure 28). There is presence of planer and trough crossbeds in the study area.

Figure 27: Laminated heterolytic unit

Figure 28: Crossbedded sandstone unit as seen at Amaozara

4.3.5 Mucracks

This is formed when water rich mud dries out in the air (Figure 29).

Figure 29: Showing mud cracks

4.3.6 Bioturbation

This is the process of reworking of sediments and rocks by once lived animals or plants. These include burrowing, ingestion and defecation of sediment grains. Bioturbation structures are created on the strata though the activities of the organism which could be as a result of the organism feeding on the substrate in the sediment, dwelling or living in the rock, burrowing to get materials to build its home etc. Unit A is highly bioturbated with the presence of vertical and horizontal burrows Orphomophia and skolithosichnofacies (Figure 30 and 31)bioturbation are clearly observed in sandstone outcrops around the study area. Orphomophia burrow is a typical feature of the Nkporo Afikpo Sandstone.

Figure 30**:** Bioturbation as seen in Unit A, (**a**) at Macregor hill, (**b**) at Ebonyi hotel

Figure 31: Bioturbation on slightly ferruginized sandstone unit opposite Romec hospital, Ndibe road.

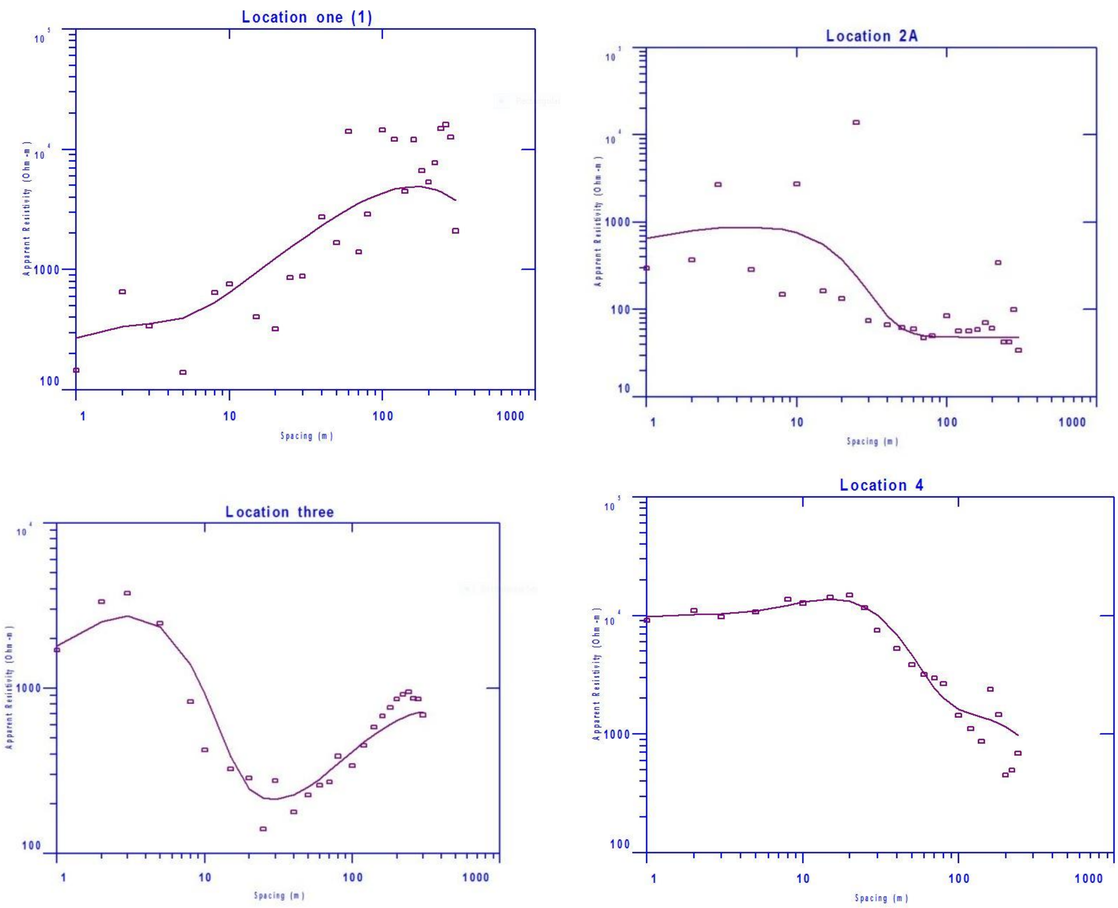
4.3.7 Iron concretions and nodules

Iron concretions are pronounced within Unit B. The iron concretions are believed to be composed of iron oxy-hydroxide, limorite (FeOCOH) nH_2O, hematite $Fe_2\ O_{3,}$ magnetite $Fe_{O}4$, and goethite FeO(OH). The iron concretions are formed from ferruginization of pre-existing sediments by chemical alteration. These iron minerals also occur in form of nodules which may be semi-rounded or irregular and may vary size and may develop into solution cavities (Figure 31 and 32).

Figure 32**:** Ferruginized solution cavities as seen in Ukpa area

4.4Petrophysical Evaluation

Geo-electric model (Figure 34) generated from the interpretation of the processed resistivity curve show a 3-6 layer model.The Geo-electric cross-section (Figure 34) shows a correlation of the top most part of the study area, it extends from Ebonyi Hotel (VES 1) through Ukpa (VES 3) and Mata hospital area (VES 4), and finally to Ozizza (VES 5). It can be observed that the sandstone thickened towards the centre of the basin from Ebonyi hotel. The thickening of the sandstone facies is followed by a corresponding thinning of the shales which eventually thins out completely at Ozizza area. The maximum thickness of the sandstone facies is observable in Ozizza area with the absence of the intermediate shale layer which was observed in VES 1, 3 and 4. The blue outline (Figure 34) indicates highly saturated sandstone unit.



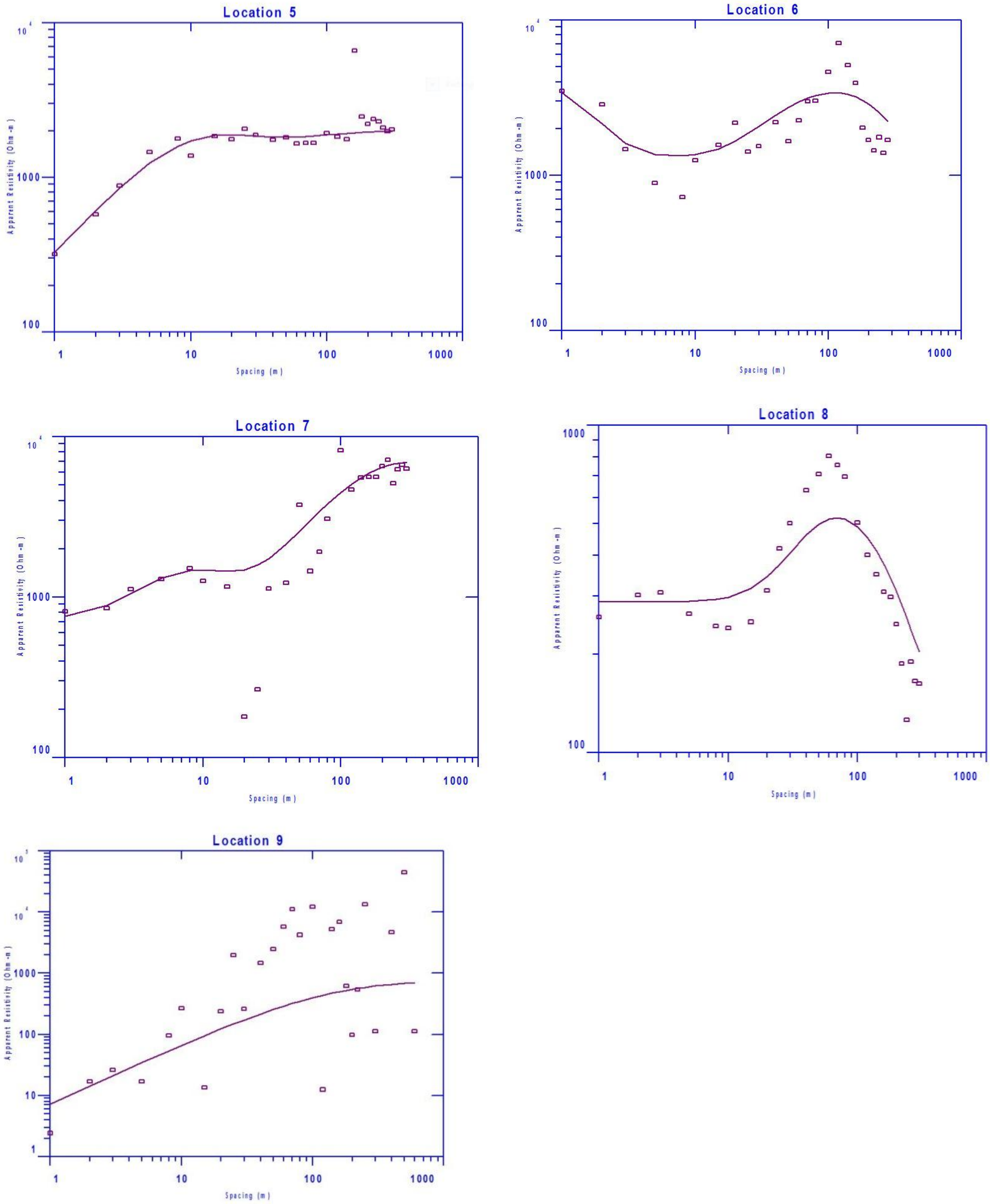


Figure 33: Processed Resistivity curves

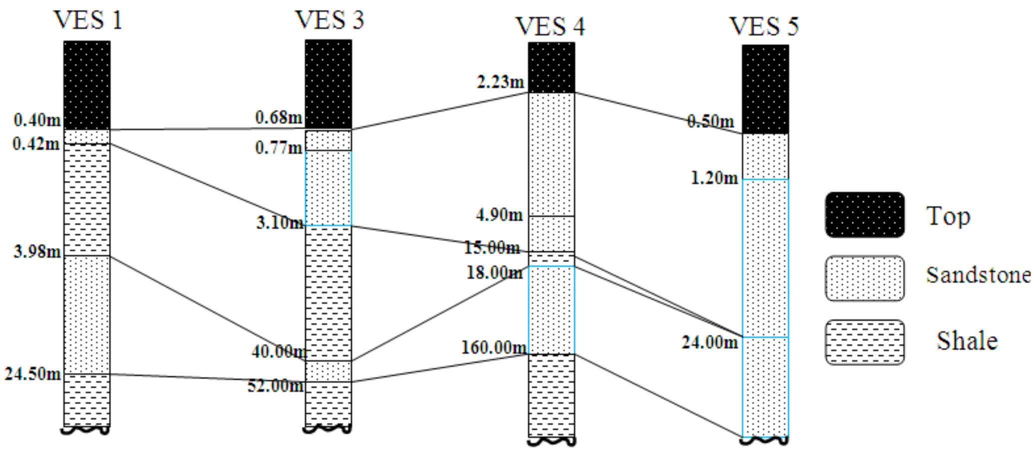


Figure 34: Geo-electric cross-sectional model

Table 11:VES locations and their respective grain size

VES LOCATION	GRAIN SIZE
VES 1 (NYSC ROAD)	1.08
VES 2 (ECHARA, MGBOM)	1.67
VES 3 (MATA ROAD)	1.77
VES 4 (OZIZZA ROAD)	0.51
VES 5 (OZIZZA SEC. SCH.)	1.36
VES 6 (AMAOZARA SAND MINE)	1.90
VES 7 (OPP. EHUGBO TECH. COL., NDIBE ROAD)	0.48
VES 8 (ORSHIVINE RIVER ROAD)	1.14
VES 9 (UNWANA ROAD)	0.53

Table 12: Summary of petrophysical results

m = 1.5, $g = 9.8ms^{-1}$**, a = 0.62,** $\delta_w = 1000kg/m^3$, $\mu = 0.0014kg/m.s$, $\rho_w = 425ohm.m$

VES POINT	ρ (ohm-m)	h (m)	F_a	∅	K (m/day)	T (m/day)	S (mS)	TR (ohm-m^2)
1	20,910	20.52	49.20	9.87	556,010	11,409,325.2	0.00098	429,073
2	998	8.19	2.35	1.28	2,920,820	23,921,515.8	0.00820	8,174
3	10,985	12.00	25.85	6.42	1,072,190	12,866,280.0	0,00109	131,820
4	1,800	142.00	4.24	1.92	6,566	932,372.0	0.07900	932,372
5	2,000	276.00	4.71	2.05	45,423	12,536,748.0	0.13800	552,000
6	6,500	65.50	15.29	4.53	64,593.2	4,230,854.6	1.01008	425,750
7	50,000	31.00	117.65	17.63	180,271	5,588,401.0	0.00062	1,550,000
8	29,000	2.00	68.24	12.30	735,840	1,471,680.0	0.00007	1,471,680
9	750	299.61	1.76	1.06	1,805,076	224,707.5	0.40000	224,708

The grain sizes gotten from the sieve analysis range from 0.48 to 1 which implies Afikpo Sandstone is medium to coarse grained (Table 11). The grain size, shape and sorting influence the void volume and shape thus the porosity and transmissivity. Beach sands are better sorted than river channel sands. This is due to the higher intensity of reworking which beach sediments undergo under the influence of tides. The percentage cumulative weight curves for beach sands tends to be steeper than river channel sands. (Friedman and Sanders, 1978). This is due to the poor sorting of the river channel sands. The cumulative weight plot for the Afikpo Sandstone units are not steep (Appendix 1-14) and therefore suggest that they are river sands deposited by traction, suspension and saltation. Some rivers and glacio-fluvial regimes have extremely poorly sorted to very poorly sorted sands with sorting values ranging from 1.00 to 2.60 while rivers and some in land dunes have moderately sorted sands with sorting values ranging from 0.50 to 1.00 (Folks and Ward, 1957). The sorting values of Afikpo Sandstone from the sieve analysis ranges from 0.50 to 1.17 which overlaps with the range of rivers and inland sand dunes. Skewness is a useful tool in deciphering environmental mixing and depositional process. The Afikpo sandstones are very positively to negatively skewed which implies that it is from a mixed environment of sand dominance (i.e. Continental with little marine influence). The Afikpo sandstones have a general grain size which ranges from medium to coarse grained.

The nature of Afikpo Sandstone shows that it was deposited in a fluctuating energy regime from low to high velocity of depositing media evident from the sedimentary structures, grain size distribution and the calculation of the statistical parameters which shows that the sandstones are medium to coarse grained, poorly-moderately sorted, positively to very positively skewed and mesokurtic to very leptokurtic. The Trace fossils seen on the sandstone (Orphiomorphia and skolithosichnofossils) are indications of shallow marine environment of high to moderate energy sublithoral environment. This shallow marine nature is further supported by the predominance of sandstone units within the formation, abundance of burrowing organisms and widely distributed pebbles. The presence of dark grey to black shales however indicates the presence of organic rich sediments deposited in oxygen deficient low energy environment. An oxygen deficient environment provides the proper condition for the formation of sulphide minerals such as pyrite and gypsum. This anoxic condition could have been generated by the Transgression during the Campanian. This implies that the sandstones and shales of the Afikpo Formation were deposited in a cycle of Regression and Transgression episodically.

The poorly sorted and medium grained sandstones (VES 3 and 6) have relatively high bulk resistivity 0f 10,985 ohm-m and 6,500ohm-m as observed in Mata road and Amaozara sand mine respectively. This suggests that there is low fluid saturation which could be as a result of poor transmissivity as seen in table 4. The moderate to well sorted and medium – coarse grained sandstones have a greater fluid saturation which is responsible for the recorded values of resistivity in sandstone unit in EcharaMgbom, Unwana and Ozizza areas, the resistivity values ranges from 750ohm-m to 2000ohm-m. It can be observed that there is higher fluid saturation in sandstones unit in EcharaMgbom, Mata road, NYSC road, Ozizza, and Ndibe Beach Road area.

An average of 8.210 was recorded for hydraulic conductivity of Afikpo sandstone. Based on Bear's standard in 1972 (Table 13), Afikpo sandstone is a very pervious unit which can serve as a prolific reservoir rock or an aquifer. The resistivity curves are of types A, Q, HK, and AK dominantly. The grain sizes gotten from the sieve analysis ranges from 0.48 to 1.90. A minimum bulk resistivity of 750 ohm m and a maximum bulk resistivity of 50,000 ohm m were recorded for Afikpo Sandstone from the inversion of the resistivity data. An average of 32.14 was evaluated to be the formation factor of Afikpo Sandstone which gave rise to porosities ranging from 1.06 to 17.63 as gotten from Archie's equation. Afikpo Sandstone was gotten to have a minimum thickness of 2m and a maximum thickness of 299.61m. Hydraulic conductivity which defines the permeability of the unit was gotten to range from 6.5×10^3 to 2.9×10^6 m/day which makes it a very good pervious unit which can serve as a prolific reservoir rock or an aquifer. Transmissivity which varies with thickness of the unit was gotten to range from 2.2×10^5 to 2.3×10^7 m/day. Figure 35 shows a porosity distribution model for the study area. It is observed that the centre of the basin has a higher porosity and reduces outwards. This is also directly proportional to the observed grain sizes. Rocks with fine/muddy (i.e smaller grain size) materials then to give rise to rocks with lower porosity and permeability. It can be observed from Table 11 and 12 that the higher the grain sizes, the better the porosity and permeability of the rock.

Table 13: Standard for hydraulic conductivities (modified from Bear, 1972)

K (m/day)	10^5	10^4	10^3	10^2	10	1	0.1	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Relative Permeability	Pervious				Semi pervious				Impervious			
Reservoir /Aquifer property	Good					Poor				None		

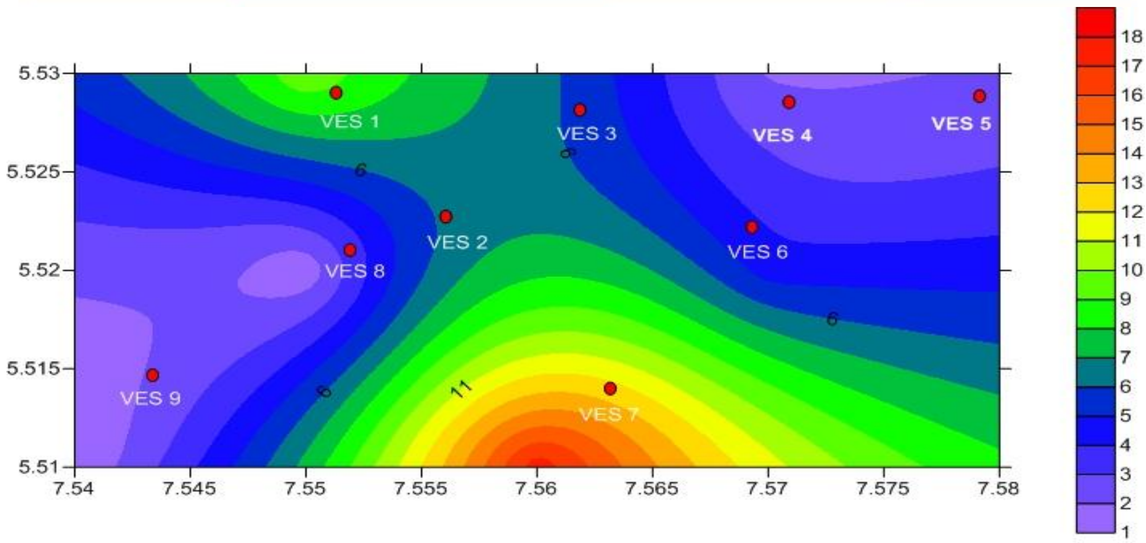


Figure 35: Porosity model of sub-surface pervious horizon

V. CONCLUSION

Based on the results gotten from the applied methods, the study area has Afikpo Formation and Mamu Formation as its main geologic unit. Mamu Formation overlies Afikpo Formation conformably. Afikpo Formation grades upwards in a coarsing upward sequence. The study area was intruded by a dolerite sill believed to have occurred in the Eocene. The dolerite sills have a trend of NW-SE and occur as pillow lavas. The lithologic units consist of syn-depositional and post-depositional joints and fractures with general trend in NW-SE and NE-SW. The formations in the study area are generally unconsolidated to slightly consolidated and have calcite material as their cementing material except in cases where iron oxide replaces the calcite due to ferruginization. Afikpo Sandstone unit are deposited by river systems and have moderately to poorly sorted sediments. Afikpo Sandstone sediments are formed from dominantly continental provenance with fluctuating energy regimes from low energy giving rise to the fine grained and laminated sandstone facies and as the energy rises, a more coarser, crossbedded unit is formed. Afikpo Formation was deposited in a shallow marine environment with influx of marine sediments and predominantly continental sediments. The sandstone lithofacies were deposited by regression while the shale lithofacies were deposited by transgression believed to have occurred during the Campanian-Maastrichtian time.

The grain sizes range from 0.48 to 1.90 which implies that the rocks are medium to coarse grained. A minimum bulk resistivity of 750 ohm-m and maximum bulk resistivity of 50,000 ohm-m was recorded for Afikpo sandstone. The proportion of clay matrix in the rock and the degree of saturation are two basic influences to the resistivity values recorded. An average of 32.14 was evaluated to be the formation factor of Afikpo sandstone, giving rise to porosities ranging from 1.06 to 17.63. It was observed that the porosity increased with increase in grain size relative to the clay content of the rock unit. Afikpo sandstone was gotten to have a minimum thickness of 2m and a maximum of about 300m. Hydraulic conductivity and Transmissivity, which defines permeability, ranges from $6.5 X 10^3$ to $2.9 X 10^6$ m/day and $2.2 X 10^5$ to $2.3 X 10^7$ m/day respectively. From these values, it can be deduced that Afikpo sandstone can serve as a prolific reservoir rock in down dip areas or an aquifer. It is also observed that surface resistivity measures can be used to extrapolate petrophysical properties of rock units in the absent of well information.

ACKNOWLEDGEMENTS

Special recognition goes to Nick Hoggmascall for his support and contributions to the research work. We are thankful to Clean Water Geoscience solution for their technical support all through the course of this work. We are also grateful to the anonymous reviewers of this work for their suggestions and comments.

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Nworie, C. David, et. al, "Geological and Petrophysical Evaluation of Afikpo Sandstone In Afikpo Sub-Basin, Southeastern Nigeria Using Integrated Approach." *International Journal of Engineering Science Invention (IJESI)*, Vol. 10(05), 2021, PP 07-34. Journal DOI- 10.35629/6734