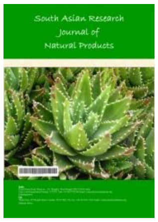

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Impact of Sandstone Maturity on Groundwater Resistivity in Geophysical Groundwater Exploration in Parts of Edo Central and Agbor, Delta State, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Author AI designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Author SS managed the analyses of the study. Both authors read and approved the final manuscript.

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ABSTRACT

Several geoscientists have concluded that some terrains have no water by simply taken very high resistivity layers in the subsurface as a dry zone in areas with sandstone aquifer. However, this present work intends at ascertaining the reasons high resistivity sedimentary areas give high yield aquifer. Eighteen rock samples from aquifers that underlie the study area were obtained. Petrographic study was done on eleven sandstone samples, two igneous, three gneiss and two schist collected from the boreholes. The maturity indexes of the sandstones were computed. Vertical Electrical Sounding was conducted at each point to determine the subsurface resistivity and the wells were drilled to depths at which aquifers were encountered. The aquifer depths were correlated with the VES and petrographic results. The results of the petrographic showed that the sandstones are arenite and wacke sandstone aquifers. The VES result showed that arenite aquifers gave high resistivity, ranged from 5900Ωm to 15000Ωm signature while wacke gave low resistivity signature, ranged from, 37Ωm to 80Ωm and both gave good water yield at these depths. This study has shown that arenites are second cycle sediments that have high percentage of quartz mineral while wackes are rich in feldspar than arenites. Weathered feldspar

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isgood conductor of electricity in the presence of fresh water, which is the reason for their low resistivity value while quartz has high resistivity that makes arenite aquifers to give high resistance.

Keywords: High resistant minerals; first cycle sediments; wacke sandstone aquifer; arenite sandstone aquifer.

1. INTRODUCTION

High resistant minerals to weathering are minerals which are not readily weathered during transportation of sediments by sedimentary cycle. They include quartz, garnet, muscovite, zircon, etc. These minerals often survived weathering processes even if it involves a very long distance of transportation unlike low resistant minerals (clay minerals and feldspars minerals) that cannot withstand long distance. These minerals are deposited into the basin as unaltered residual fragments of a precursor rock body during sedimentary cycle.

First-cycle sediments are dominated by the presence of low resistant minerals (Clay and feldspars minerals)and less resistant minerals because they are often known to have been transported through a short distance in many cases. When these sediments are reworked through a second or more cycles, the low-resistant minerals will be eliminated thus, the second cycle sediments will be dominated with high resistant minerals, because the sediments have been transported through a very long distance, hence only high resistant minerals can withstand such long distance. The number ofcycles sediment has passed through determines its contents and the percentage of high resistant and low resistant minerals present, as well as its maturity.

Apparent resistivity of a geological material is determined from Ohm's law by simply measuring the electrical resistivity of the material. Resistivity is directly related to temperature, salinity in the porous media, and mineral constituents of the material [1,2,3]. Electrical field strength, E at a point in a material is proportional to the current density, j as shown in Equation (1).

$$E = \rho j \qquad (1)$$

The proportional constant, ρ is called apparent or specific resistivity.

Similarly, ρ can be related to the ratio of potential difference to the current that flows across the material as shown in Equation (2).

$$\rho = \frac{\Delta V}{I} \qquad (2)$$

In geophysical exploration of groundwater, direct current sounding such as the Schlumberger array is often used. Current is injected into the ground via current electrodes at the surface and the potential difference between the current electrodes and is measured. Generally saturated geological materials in the subsurface often give sharp drop in the resistivity values as a signal for water accumulation in the porous zones within the rock unit. Commonly, the resistivity of a fresh groundwater saturated igneous and metamorphic rocks ranges from 10Ωm to 100Ωm [4] while saturated sandstone and siltstone fresh water aquifer (sedimentary rock) ranges from 15Ωm to10^4Ωm [5,6]. At a temperature of 0 to 200°C, the resistivity of an aqueous solution decreases with increasing temperature [7]. Dakhnov [8] described the relationship of temperature and resistivity as:

$$\rho_w = \frac{\rho_{wo}}{1+\alpha(T-T_o)} \qquad (3)$$

where, ρ_{wo} = Resistivity of the fluid at T_o, α =Temperature coefficient ratio.

There is large variation in electrical conductivity in wet samples with pressure to only 6 kbars [9,10]. This alteration may be attributable to changes inpore volume and crack connectivity with pressure, but much more work has yet to be done particularly with the additional complication of temperature as a variable [11]. Water under high pressure and high temperature becomes very conductive (more than 0.01 mho/m at 200°C and 10 kbar), in some cases becoming more conductive than many rocks under similar conditions of temperature and pressure [12]. As the resistivity of igneous rocks decreases from 100Ωm to 27Ωm, the percentage of water saturation in the porous zones of the igneous rocks increases 24% to 100% as shown in Fig. 1. Whereas in the normal resistivity range of groundwater in a rock mass, the resistivity of rocks was influenced by their intrinsic matrix resistivity more than by pore fluidResistivity [13].

One of the key indicators to where groundwater is accumulated or occurred (aquifer) within the bedrock in the subsurface during geophysical exploration is a sharp drop in the resistivity values which often ranges from 20 to 100Ωm in igneous and metamorphic rocks [4,3]. However, it has been reported in literatures that high resistivity zones in sedimentary terrain has aquifer when drilled while some took such high resistivity zones as dry zones.

Hence this present work is aimed at investigating the impacts of sandstone maturity on groundwater resistivity and to ascertain the reason(s) for resistivity disparity in sandstone aquifer.

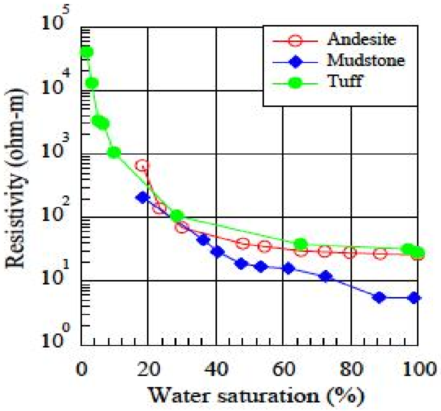

Fig. 1. Relationship between resistivity of a rock and water saturation of igneous rock and mudstone after [3]

2. MATERIALS AND METHODS

Eighteen samples of rock cuttings from the aquifers that underlie the study area were cut into thin sections for petrographic study using petrographic microscope. Eleven of the samples were sandstones while the remaining seven were from basement rocks (igneous and metamorphic rocks). This was done to be able to delineate minerals that make up the aquifers in the study area. Eighteen Vertical Electrical Sounding (VES) were conducted across the eighteen points in the study area where the samples of aquifers were collected to delineate the resistivity of the aquiferous unit in each point using Schlumberger array.

Thereafter, sophisticated India rig that uses both air and water was used to drill each point. The drilling exercise was carefully monitored; the depth at which water began to flow out was correlated with the same depth on the inversion model resistivity curve using Res1Dinvers in order to properly identify the resistivity values of aquiferous zones in each well. Maturity index of each sandstone sample was calculated using the method of Nwajide and Hoque [14], and correlated with the resistivity values of each aquifer. The information from both the petrographic study and geophysical study (VES) of rock unit that make up the aquifers in the study area were analyzed to properly delineate the impact of sandstone maturity on resistivity values of groundwater within the aquifers.

3. RESULTS AND DISCUSSION

3.1 Petrographic Results of the Aquifers in the Study Area

Petrographic result of the sandstone samples obtained from the drilled borehole at Ekpoma, Uromi, Ubiaja, Ewohimi, and one sample from Agbor showed that quartz ranged from 93% to 97% except Irrua that was 75% as shown in Table 1. Feldspar (F) and rock matrix (Rf) ranged from 1 to 3% except for Irrua that was 23% feldspars and 2% rock matrix. Hence they are all classified as quartz arenite arkosic arenite for Irrua according to Pettijohn [15] classification of terriginous sandstones. Their maturity index ranged from 3 to 24 (Table 1). However, one sample from Agbor, Aya, Illushi have quarz percentage ≤ 70% while the feldspar and rock matrix are higher than arenite. Their Maturity index was observed to be very low (less than 3) compare to arenite. Hence they are classified as wacke (feldspar geywacke and arkosic wacke) (see Table 1).

The sandstone samples that are classified as arenite under thin section gave well roudded to rounded shapes as shown in 2a to 2k except for 2d, and 2i which are wacke, they are fragmented and sub-angular (see Fig. 2).

The petrographic result of rock samples from Okpella showed that the aquifers are made up of igneous rock, biotite hornblende granite porphyry (see Table 2). Otuo aquifers comprise augen and biotite gneiss, Igarra, Ikpeshi, and Kabba comprise gneiss, schist, and gneiss respectively. The result of the thin section showed that the rocks in these areas are rich in high percentage of feldspars, plagioclase than quartz (Fig.3 and Table 2).

Table 1. Petrographic result of sedimentary rock samples' cuttings from the aquifers in the study area

S/n	Locations	Rock type	Mineral contents (%)			MI= Q/(F+RF)	Rock name
			Q	F	Rf		
1	Ekpoma	sandstone	96	1	3	24	Quartz arenite
2	Ekpoma	Sandstone	97	1	2	32	Quartz arenite
3	Irrrua	Sandstone	75	23	2	3	Arkosic arenite
4	Uromi	Sandstone	93	3	4	13.3	Quartz arenite
5	Uromi	Sandstone	95	2	3	19	Quartz arenite
6	Ubiaja	Sandstone	96	1	3	24	Quartz arenite
7	Ewohimi	Sandstone	93	2	5	13.3	Quartz arenite
8	Aye	Alluvia	70	25	5	2.3	Feldspar greywacke
9	Illushi	Sandstone	37	49	16	0.57	Feldspar greywacke
10	Agbor	Sandstone	95	2	3	19	Quartz arenite
11	Agbor	sandstone	50	35	15	1	Arkosic wacke

Q= quartz, F= feldspar, RF= rock fragment

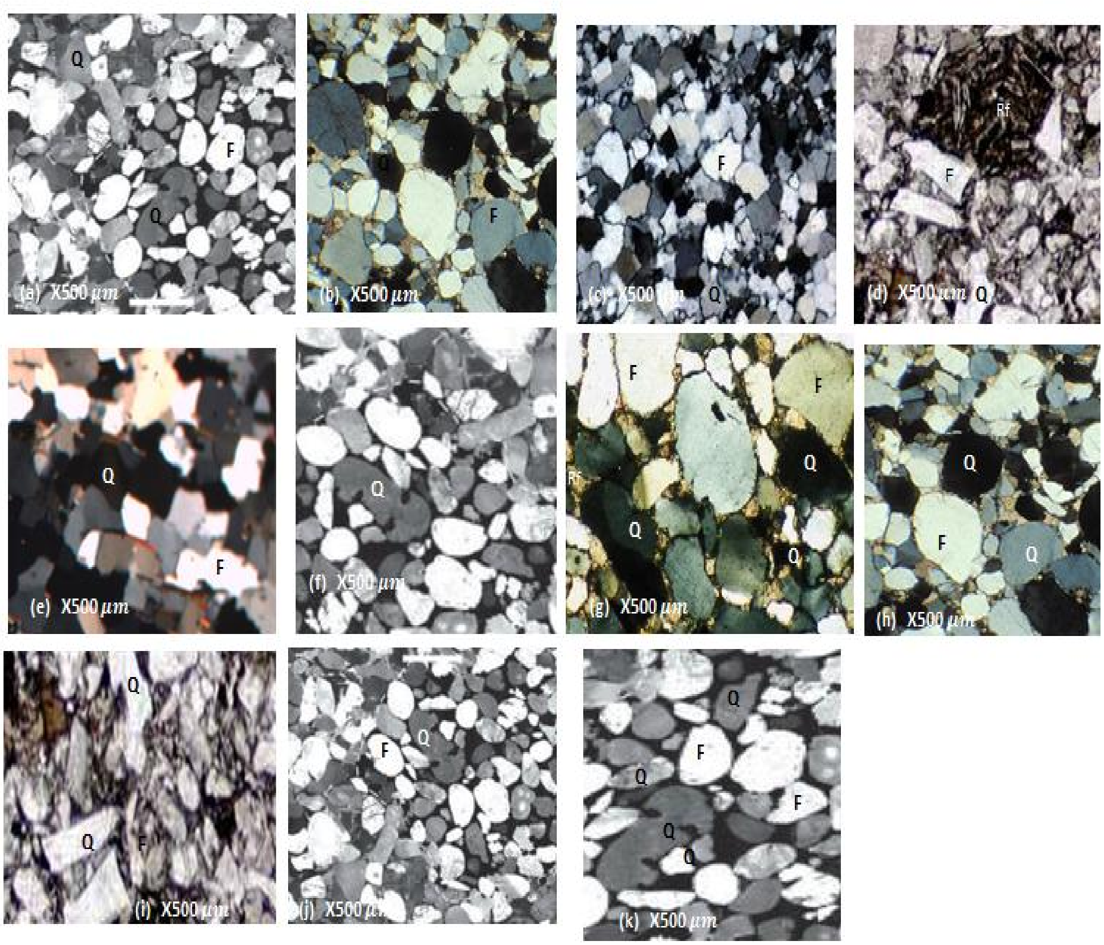

Fig. 2. Thin section for the sandstone aquifers in the study area

(a) sample of sandstone from Ekpoma, (b) Sample of sandstone from Ekpoma, (c): sample of sandstone from Irrua, (d)Sample of sandstone from Aya, (e) Sample of sandstone from Agbor, (f) Sample of sandstone from Agbor, (g) Sample of sandstone from Ubiaja, (h) Sample of sandstone from Uromi, (i) Sample of sandstone from Illushi, (j) Sample of sandstone from Uromi, and (k) Sample of sandstone from Ewohimi

Table 2. Petrographic results of igneous and metamorphic rock samples' cuttings from the aquifers in the study area

S/n	Locations	Rock type	Mineral contents	Rock name
1	Okpella, Edo	Igneous	Q, F, Horn, Bio, Plag	Biotite hornblende granite porphyry
2	Okpella, Edo	Igneous	Q, F, Horn, Bio, Plag	Biotite hornblende granite porphyry
3	Otuo, Edo	Metamorphic	Q, F, Augite, Bio, Plag	Augen gneiss
4	Otuo, Edo	Metamorphic	Q, F, Bio, Plag	Biotite gneiss
5	Igarra, Edo	Metamorphic	Q, F, Bio, Plag	Biotite schist
6	Ikpeshi, Edo	Metamorphic	Q, F, Bio, Garn, Musco, plag	Muscovite-biotite garnetiferous Schist
7	Kabba, Kogi	Metamorphic	Q, F, Horn, Bio, plag	Biotite gneiss

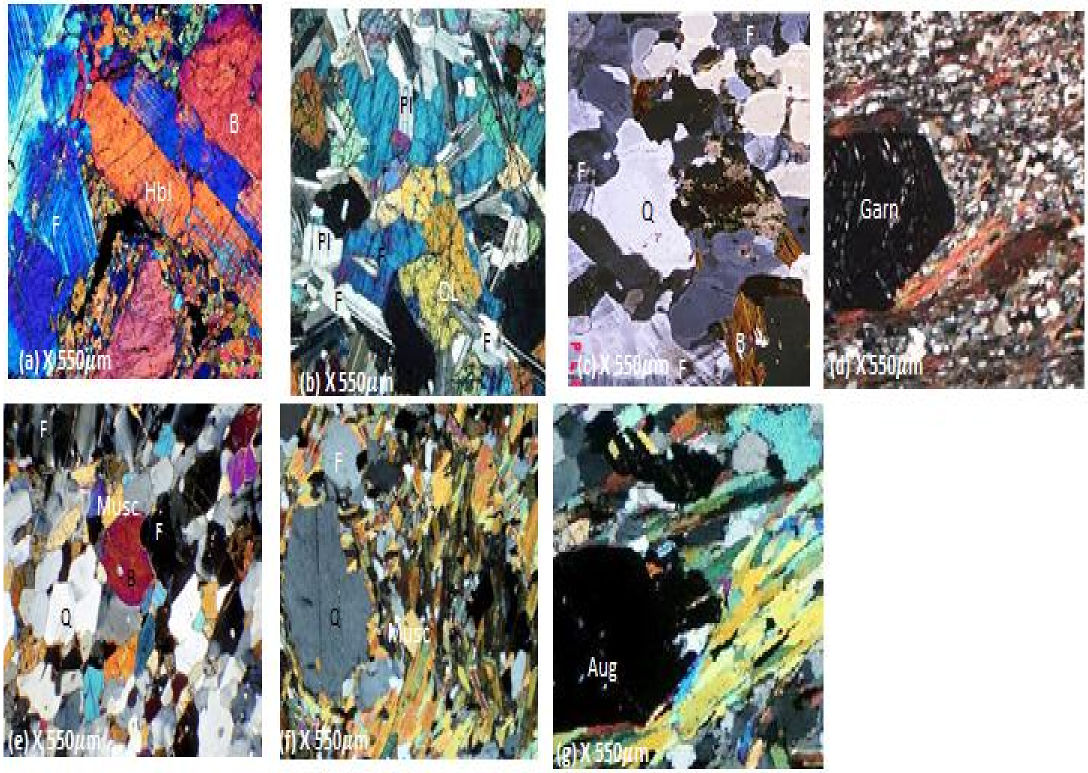

Fig. 3. Thin section for the basement rock aquifers in the study area

(a) sample from Okpella, (b) sample from Okpella, (c) sample from Kabba, (d) sample from Ikpeshi, (e) sample from Otuo, (f) sample from Otuo, sample from Igarra

3.2 Resistivity Results of the Aquifers in the Study area

The result of VES in Ekpoma, Uromi, Irrua, Ewohimi, Ubiaja, and One of the samples in Agbor area showed that the sandstones aquifers are arenite with very high resistivity values that ranged from 5,900Ωm to over 15,000Ωm and their curve types are commonly A, AQ, and QHA as shown in Fig. 4. The total depth of each aquifer is 295m, 250m, 270m, 225m, 275m, and 105m respectively. However, sandstone samples from Illushi, Aya, and one of the samples from Agbor are wacke sandstones that make up the aquifers. They have very low resistivity values compared to the previous ones, ranged from 37Ωm to 80Ωm and their curve types are commonly AQ and QHA (Fig. 4). The total depths for the aquifers are 70m, 25m, and 95m respectively.

The VES results for the igneous and metamorphic rock aquifers in the study area showed that the resistivity values of the aquifers are generally low. It ranged from 30Ωm to 82 Ωm with resistivity curve types that are majorly A and QHA (Fig. 5). Aquifers that showed A curve type are mainly aquifers that occurred within thick over burden while those that showed QHA curve type are fractured and weathered aquifers. The depths of aquifer occurrence ranged from 30m to 45m.

3.3 Impact of Sandstone Maturity on Groundwater Resistivity in a VES Survey

The correlation of petrographic study of all the sandstone samples, schist, igneous, and gneiss results within the aquifers in the study area with their resistivity results gave clear understanding that the higher the percentage composition of quartz mineral compared to feldspars and rock fragment in the samples of rocks that constitute the aquifer, the higher the values of their resistivity and vice versa (See Table 3). The higher the maturity index (3 to over 19), the more the sandstone becomes matured, the more the percentage of quartz mineral, and the higher the resistivity value. Because aquifers in Ekpoma are super mature thatis the reason their aquifers' resistivity values are the highest among the arenite aquifers. However, sandstone aquifers from Aya, Ilushi, and Agbor that are wacke (that is the percentage of feldspars mineral and rock fragment are more than quartz) have very low resistivity values (37Ωm to 80Ωm compare to arenite aquifers (table 3). This observation is because feldspar mineral has good conductivity while quartz is a bad conductor of electric current. The more the content of quartz in aquiferous layer, the higher the value of the resistivity amid fresh water or saturation.

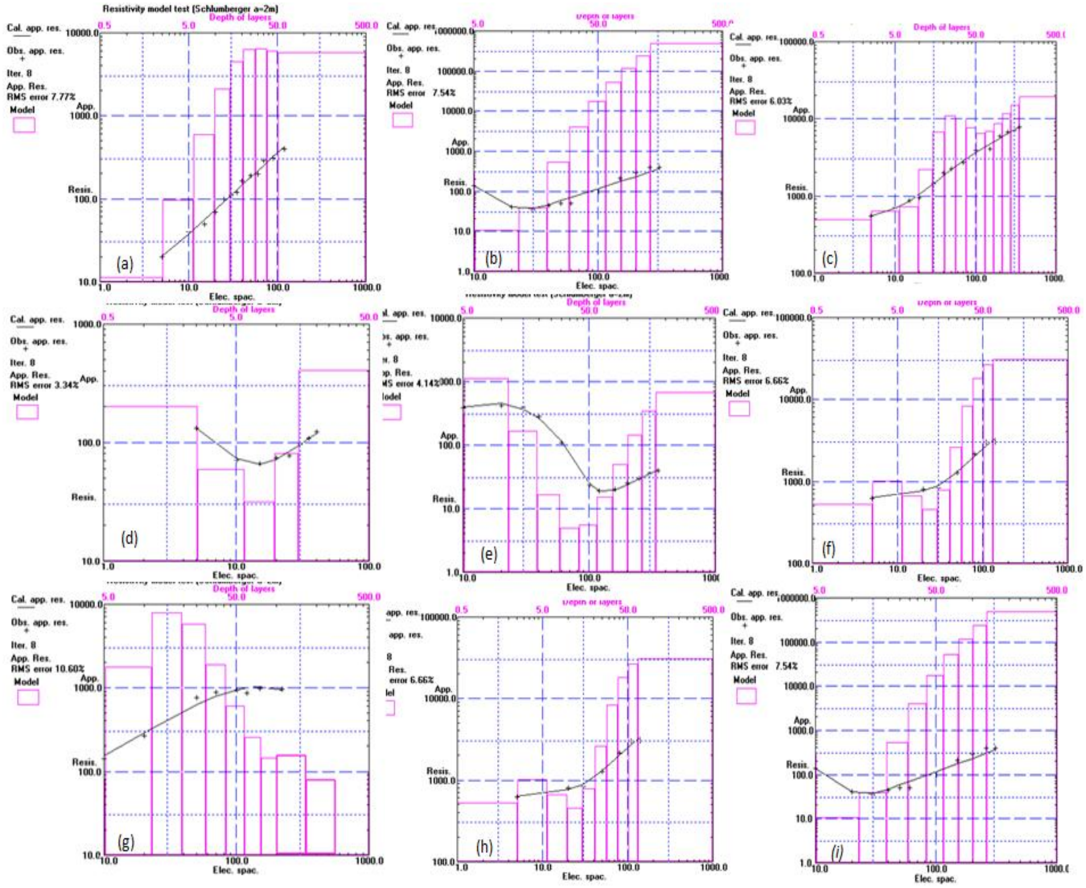

Fig. 4. Inversion models for the field resistivity data acquired in the study area
(a) model for Ekpoma, (b) model for Ekpoma, (c) model for Ubiaja, (d) model for Aya, (e) model for Agbor, (f) model for Agbor, (g) model for Ilushi, (h) model for Uromi, (i) model for Uromi aquifer

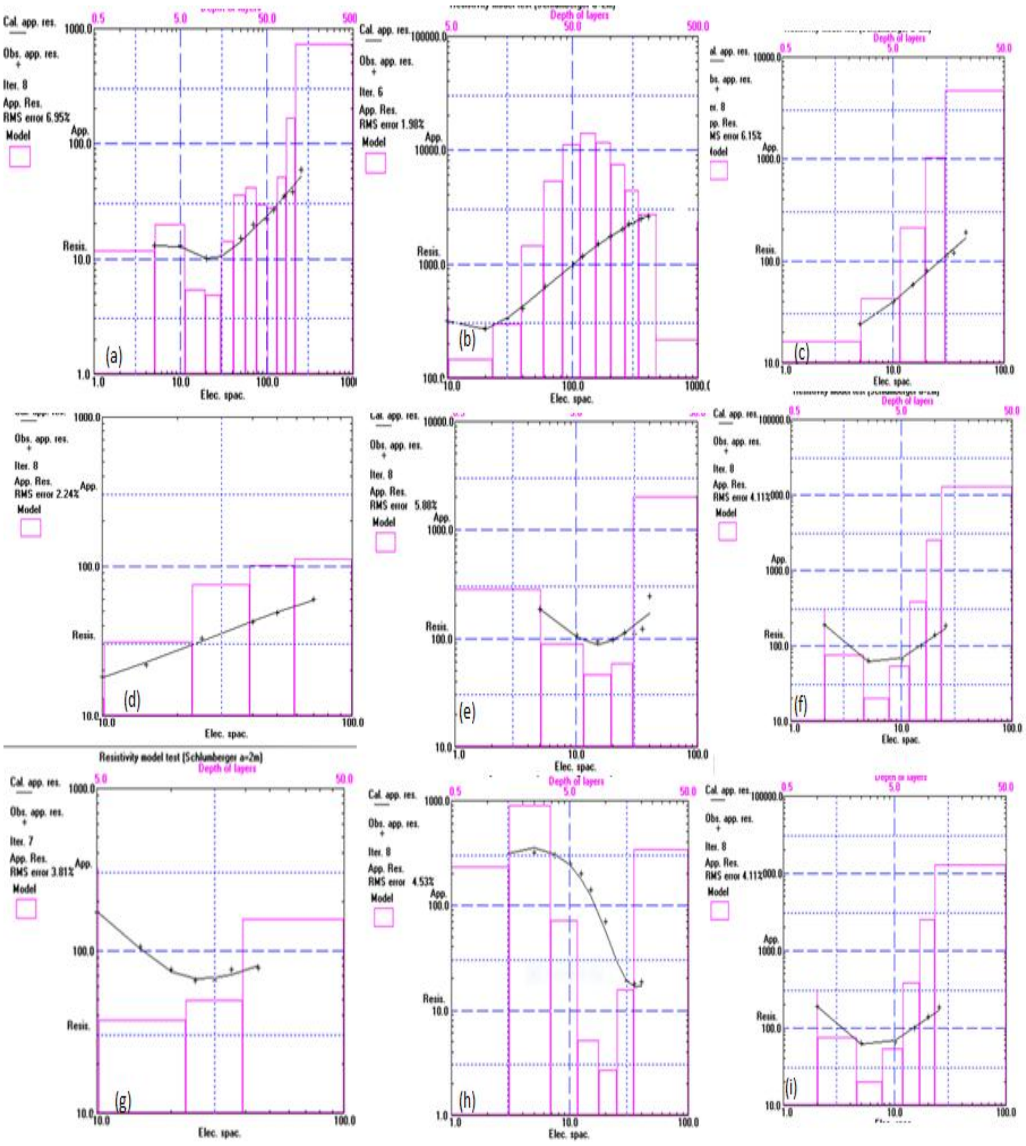

Fig. 5. Inversion models for the field resistivity data acquired in the study area

(a) model for Ewohimi, (b) model for Irrua, (c) model for Kabba, (d) model for Ikpeshi, (e) model for Otuo, (f) model for Otuo, (g) model for Igarra aquifer

Sandstone aquifers (Ekpoma, Irrua, Ewohimi, Uromi, Ubiaja, and Agbor) in the study area with high percentage of quartz, very low percentage of feldspars, and rock fragment must have been sediments of second or third cycle that is, they have been re-cycled and traveled for a very long distance before they are deposited as aquifers. As a result of this, the feldspars mineral has been weathered and washed away because of its inability to travel long distance and withstand stress thus quartz that can withstand stress of long distance becomes more predominant in the aquifer. However, sandstone aquifers in Ilushi, Aya, and one of the samples from Agbor, showed very low resistivity signature, 37Ωm to 80Ωm (See Fig. 6). This was as result of the high percentage of feldspars mineral compare to quartz, feldspar is a good conductor in the presence of fresh water. For the aquifers in these areas to have high percentage of feldspars, it means their aquifers are not re-cycle sediment, that is they are first cycle sediments (Their provenance is very close to their point of deposition), the feldspars have not been destroyed and are not weathered yet.

Table 3. Correlation of Aquifers with the resistivity values of aquifers in the study area

S/n	Sample Location	Rock name	MI	Maturity	Curve type	Resistivity (Ωm)
1	Ekpoma	Quartz arenite	24	Super mature	A	15000
2	Ekpoma	Quartz arenite	32	Super mature	A	10000
3	Irrrua	Arkosic arenite	3	Sub-mature	AQ	10000
4	Uromi	Quartz arenite	13.3	mature	A	5900
5	Uromi	Quartz arenite	19	mature	A	6890
6	Ubiaja	Quartz arenite	24	Super mature	A	7890
7	Ewohimi	Quartz arenite	13.3	mature	QHA	7000
8	Aya	Feldspar grewwacke	2.3	Immature	QHA	45
9	Illushi	Feldspar greywacke	0.57	Extremely Immature	AQ	80
10	Agbor	Quartz arenite	19	Mature	A	9000
11	Agbor	Arkosic wacke	1	Immature	QHA	37
12	Okpella, Edo	Biotite hornblende granite porphyry	-	-	A	60
13	Okpella, Edo	Biotite hornblende granite porphyry	-	-	QHA	30
14	Otuo, Edo	Augen gneiss	-	-	A	45
15	Otuo, Edo	Biotite gneiss	-	-	QHA	82
16	Igarra, Edo	Biotite schist	-	-	A	67
17	Ikpeshi, Edo	Muscovite-biotite garnetiferous Schist	-	-	QHA	75
18	Kabba, Kogi	Biotite gneiss	-	-	QHA	78

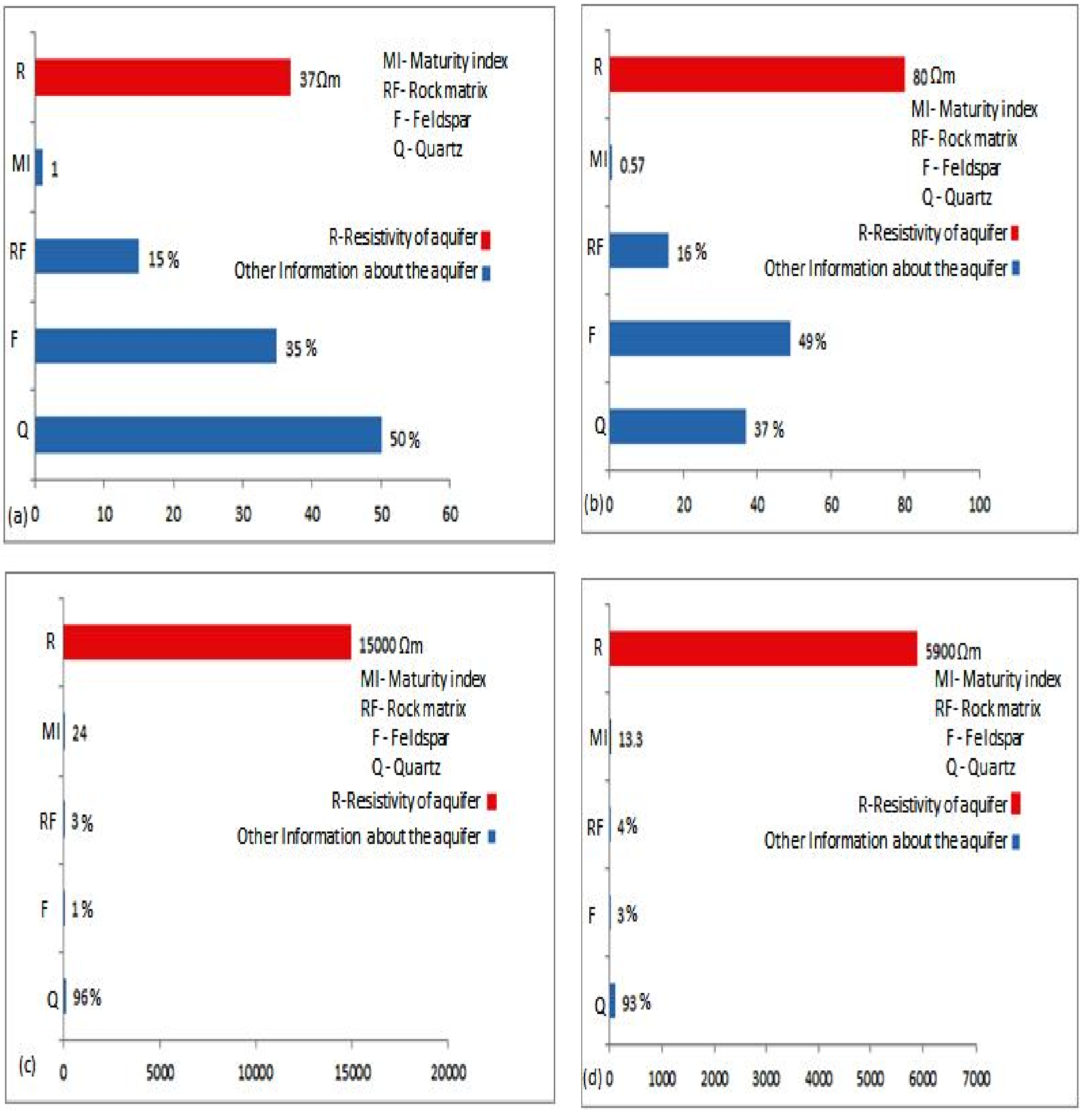

Fig. 6. Bar char for selected aquifers in study area showing plots for resistivity, maturity index, and mineral composition of the sandstone aquifers

The basement rock aquifers (Igneous and metamorphic rocks) in Okpella, Ikpeshi, Kaba, Otuo, and Igarra have low resistivity values like those of the wacke sandstone aquifers. This observation is because basement rocks are rich in feldspar and other ferro- magnesium minerals which are good conductor of electric current in the presence of fresh water.

4. CONCLUSION

A study on the impact of sandstone maturity on groundwater resistivity has been done. The study showed that arenite sandstone aquifers have extremely high resistivity values (590Ωm to 15000Ωm) than wacke sandstone aquifers that commonly have low resistivity signature (37Ωm to 80Ωm) similar to that of igneous and metamorphic rock aquifers. The reason for this disparity is that arenite aquifers have high percentage of quartz content than wacke aquifers that are predominantly feldspars mineral. Quartz has high resistant to electric current flow while feldspar has good electrical conductivity.

Reliable geophysical exploration for groundwater will be achieved ifgeophysicists and hydrogeologists have good knowledge of the geology of an area. In a typical sedimentary terrain, adequate knowledge about the sedimentary cycle is key in order not to mistaken aquiferous zone for a dry zone.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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