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Laboratory Measurements of Electrical Resistivity of Rocks from Girei Local Government Area, Adamawa State, North-Eastern Nigeria.

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Abstract

This paper presents the results of the laboratory measurements of electrical resistivity of fourteen representative surface rock samples from Girei Local Government Area, Adamawa State, part of the Yola arm of the Upper Benue trough, NE Nigeria. The effect of time of water saturation on the electrical resistivity of these rock samples was also investigated. The purpose was to provide basic data that will be used in the determination of the petrophysical characteristics and electrical conductivity mechanisms of these rocks that will further aid interpretation of down-hole, ground and airborne electromagnetic surveys in the area. The two electrode method was used for the electrical resistivity measurements. Results of the electrical resistivity of the saturated rock samples gave values ranging from 7.485 to 10.690x10^3 Ωm with an average of 8.160 ± 0.229x10^3 Ωm. The preferred orientation of the water wet pores results in low electrical anisotropy values from 1.2:1 to 1.7:1. Results further showed that resistivity decreases with increasing time of water saturation.

***Keywords*:** electrical resistivity, anisotropy, rocks, Girei.

1.0 Introduction

Electrical properties of rocks are utilized in both applied and general Geophysics. They are exploited commercially in the search for valuable ore bodies, which may be located by their anomalous electrical conductivities. Electrical resistivity is one of the most important properties of rocks for electrical surveying [1]. Electrical resistivity data can be used in the determination of petrophysical characteristics and electrical conductivity mechanisms of rocks. Since electrical method provides the best means to detect and follow fluid movement in the subsurface [2], it can be used in dam sites studies to monitor seepage/leakage [3]. Essentially, this has to do with the porosity of the underlying rocks.

Electrical resistivity is a measure of how strongly a material opposes the flow of electric current. The electrical resistivity, ρ measured in ohm-metre is given by

$$\rho = \frac{RA}{L} \qquad (1)$$

Where R is the electrical resistance of the material measured in ohms; A is the cross sectional area of the material in square metres and L is the length of the piece of the material measured in metres.

The electrical resistivity is defined as the inverse of the electrical conductivity (σ) of the material. That is

$$\rho = \frac{1}{\sigma} \qquad (2)$$

Electrical conductivity is a measure of a material's ability to conduct an electric current.

The electrical conductivity of water is usually expressed in microSiemens per centimeter (μS/cm).

$$Conductivity(\mu s/cm) = \frac{10^4}{\rho(\Omega m)} \qquad (3)$$

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The electrical resistivity of a rock depends on physical properties of the rock and the fluid it contains. Most sedimentary rocks are composed of particles having a very high resistance to the flow of electric current. When these rocks are saturated, the water filling the pores is relatively conductive compared with the rock particles or matrix. The resistivity of a rock therefore, is a function of the fluid contained in the pore spaces, the salinity of the fluid and how the pore spaces are interconnected.

Electrical conductivity in porous media or rocks bearing water is controlled by various mechanisms. The most important mechanisms are the pore fluid (ionic or electrolytic) conductivity and the fluid-solid (surface) conductivity [4, 5]. The electrolytic conductivity depends on the fluid conductivity, which is affected by the ionic composition (salinity), ionic-exchange capacity of the solid matrix and acidity- alkalinity of the pore fluid. The surface conductivity depends on the clay conductivity, which is affected by the content and type of clay, and the charge ions concentrating at the grain boundaries. In the process of electric current conduction, the surface conductivity becomes dominant when the pore fluid has a low concentration of ions (fresh water). When the pores are saturated with saline water, ionic conductivity becomes dominant, because the conduction of electric current takes place through the saline water [4]. In electrolytic conductivity, the geometry of the connected pore or crack space determines the geometry of the conductive path [6]; this includes pore geometrical properties like porosity and tortuosity. Generally, the electrical resistivity of rocks is influenced by the amount of pore fluid saturant, the nature of the pore fluid, metal content, permeability, temperature pressure and microstructural properties such as porosity, shape and size of grains.

In this study, laboratory measurements of the electrical resistivity and electrical resistivity anisotropy of rocks from the study area were performed. The aim is to provide basic data that can be used in the development of exploration strategies for aiding interpretation of down hole, ground and air-borne electromagnetic surveys. The effect of increasing the time of water saturation on the electrical resistivity was also investigated.

Location and Geology of the Study Area

Girei Local Government Area lies between latitude $9^0$00'N and $9^0$32'N and longitude $12^0$10'E and $12^0$48'E (Figure 1).The study area is part of the Yola arm of the upper Benue trough and is composed mainly of the Bima sandstone formation and quartenary alluvial materials. The Bima sandstone comprises the oldest sediments in the upper Benue trough which directly overlie the crystalline basement rocks. From the descriptions of the sequence exposed in the Bima sandstone, a three-fold subdivisions; namely: the upper Bima (B3), the middle Bima (B2) and the lower Bima (B1) were recognized [7, 8]

The upper Bima is fairly homogenous, relatively mature, fine to coarse-grained, thick-bedded sandstone with many sedimentary structures. It is widespread and may attain more than 1700m in thickness. The sequence was deposited under fluvatile to deltaic environment [7]. The late Albian to early Cenomanian age is assigned to this upper member [9].

The middle Bima (B2) is a fairly uniform unit composed of very coarse-grained, feldspathic sandstone with thin bands of clay, silts, shale and occasional calcareous sandstone. It varies in thickness from 300m to 1200m. A tentative middle Albian age has been assigned to it [9] on the basis of pollens and radiometric data obtained from intercalated lavas.

Lower Bima appears in the core of the Lamurde anticline where they consist of coarse-grained feldspathic sandstone alternating with red, purple shale and occasional bands of calcareous sandstone and siltstone. It is a highly variable unit with an over- all thickness of over 500m. An upper Aptian/Albian age has been assigned to this part of Bima sandstone [10].

Field study of the gully sites revealed that the Bima sandstones has been moderately weathered, moderately sorted, loosed and contains small portions of clays [11]. The alluvial deposit which occurs mainly along the banks of the River Benue and its tributaries consists of sands, clays, silts, silty-clays and pebble sands [11]. The sands are usually loose, moderately sorted and relatively permeable.

Methods of Investigation/ Sample Collection and Preparation

Fourteen representative surface rock samples labeled S_1-S_{14} were collected from different locations in the study area. The sample locations were determined using a 12 Channel Garmin Global Positioning System (GPS). The method used in [12] was adopted for sample preparation. Firstly, the samples were cut into rectangular shapes, each with a cross sectional area of 2cm by 2cm and a thickness of 1.5cm. This was to ensure accurate resistivity calculations. Thereafter, a lapping disk machine (or shaping-up rock machine) was used to make the surface of the rocks smooth for good electrode contact. Samples were then placed in beakers labeled Sw_1-Sw_{14} containing about 400ml of borehole water obtained from the study area to saturate them for 48 hours. A brief description of the sample types, locations, and positions are shown in Table 1.

Measurement of the Rock Resistivity

Laboratory measurement of the electrical resistivity of the rock samples were performed using the two electrode method [13, 14]. The end electrodes were made of brass plates (a highly conducting material) cut into square shapes (2cm x 2cm) and designed to cover each end of the sample perfectly well. A constant voltage (V) of 1100V was applied and the current that flows through the sample measured. About five measurements of the current (I) were made for each sample

and the mean taken. The voltage and current values were measured using the Leakage Current-Breakdown Voltage and Tera ohm-meter. The sample resistance, r_s is then obtained from the relation:

$$r_s = V/I \quad (4)$$

The resistivity, R is obtained from the equation:

$$R = r_s(A/L) \quad (5)$$

Where: A is the cross sectional area, and L the length of the sample.

Following standard procedures [12, 15], the electrical resistivity (R_o) of the rocks at 100% water saturation was measured at 24 and 48 hours after saturation with boreholes water and the mean value taken. This is to ensure that the electrical resistivity values are stable with time. Under this state, it is expected that the water has chemically equilibrated with the rock and represents in situ conditions. Before measurements, the surfaces of the rock samples removed from the beaker were first wiped with tissue paper. This action renders the saturated samples surfaces dry, so that the measured current is the current passing through the rocks.

Measurement of Resistivity of Water Samples

Water samples used to saturate the rocks were collected from fourteen functional boreholes from different locations within the study area. The conductivity of the water samples were first measured using conductivity meter at 35^0C.The resistivity, R_w of the water samples were then obtained by taking the reciprocal of the conductivity.

Electrical Anisotropy Determination

Eleven samples were chosen and tested for anisotropy, λ. Resistivity measurements were performed on the three sides (labeled α, β and γ) of the sample. The values of electrical resistivity anisotropy were obtained by taking the ratio of the resistivity value for the side showing the largest value over the resistivity value for the side showing the smallest value [16]. That is:

$$\lambda = \frac{R_O \text{ for the side with highest value}}{R_O \text{ for the side with lowest value}} \quad (6)$$

Results and Discussions

Table 2 shows electrical resistivity values for the saturated rock samples R_o, resistivity of water used for saturating the rocks R_w, and the samples porosity, Ø. R_w values were in the range of 1.01 - 26.32Ωm (0.04 - 0.99 mho). R_o ranges from $7.485X10^3$ - $10.690X10^3$ Ωm with an average of $8.160 \pm 0.229x10^3$ Ωm.

The results electrical resistivity measurements of the saturated samples showed that the conductivity of rocks depends on the saturating fluid than the minerals that formed the matrix [1, 17]. The resistivity values obtained for the saturated samples are in general agreement with established literature [6, 13, 17 and 18]. It was observed that all the samples have varying resistivity values. The variation in the values obtained is due to the differences in the concentration of ions (salinity) of the saturating liquids and the paths through which electrolytic conduction takes place. Rocks with high interconnected pores usually have lower electrical resistivity values since it allows a smooth passage of the conducting liquid. In the other hand, rocks with poor interconnected pores or tortuous paths have high electrical resistivity values owing to the uneasy passage of the conducting liquid. This further explains why care must be taken in trying to ensure tight electrical contacts, since it might lead to increase in pressure which tends to close up pore spaces, hence decreasing electrical conductivity in the rocks. Tables 3 – 16 displayed resistivity values (R_t) at various levels of time of water saturation for $S_1 – S_{14}$.

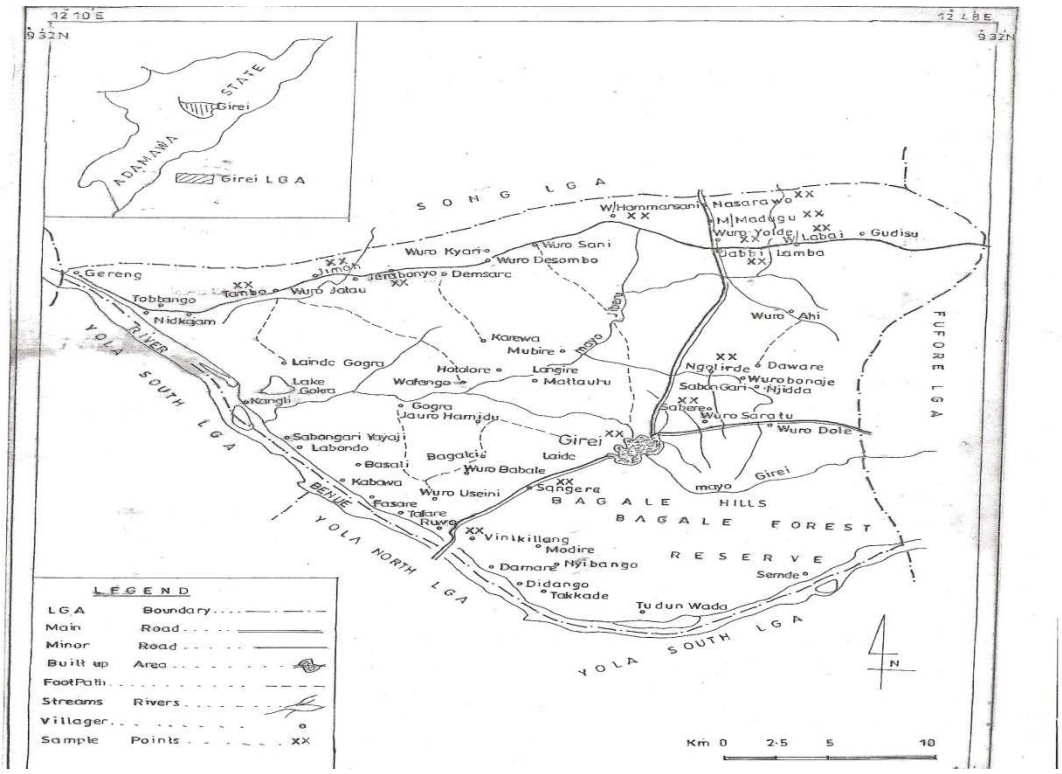


Figure 1: Map of Study Area Showing Sample Locations

Table 1: *Table showing samples description and location*

Sample	Description	Location	Latitude	Longitude
S_1	Very fine-grained sandstone	Wuro Ngolirde	$9^0$26’28.3”N	$12^0$34’07.0”E
S_2	Fine-grained sandstone	Wuro Labai	$9^0$30’14.9”N	$12^0$39’22.7”E
S_3	Limonitic feldspathic coarse-grained sandstone	Jabbi Lamba	$9^0$30’17.8”N	$12^0$36’15.1”E
S_4	Weathered conglomerate	Nasarawo	$9^0$31’22.7”N	$12^0$33’47.6”E
S_5	Weathered coarse-grained sandstone	Mallam Madugu	$9^0$31’12.4”N	$12^0$34’11.5”E
S_6	Limonitic medium-grained sandstone	Wuro Yolde	$9^0$30’46.8”N	$12^0$34’30.0”E
S_7	Limonitic coarse-grained sandstone	Tambo	$9^0$29’59.8”N	$12^0$20’59.9”E
S_8	Slightly ferrigenise coarse-grained sandstone	Jimoh	$9^0$29’12.7”N	$12^0$23’05.7”E
S_9	Feldspatic ferrigenous sandstone	Jera Bonyo	$9^0$29’40.9”N	$12^0$26’54.2”E
S_{10}	Fine-grained sandstone	Wuro Hamsani	$9^0$31’27.8”N	$12^0$31’50.5”E
S_{11}	Medium-grained sandstone	Sabere	$9^0$23’53.4”N	$12^0$33’26.2”E
S_{12}	Coarse-gritty sandstone	Girei	$9^0$21’09.1”N	$12^0$31’46.8”E
S_{13}	Medium-grained sandstone	Sangere (FUTY)	$9^0$19’47.4”N	$12^0$29’47.3”E
S_{14}	Coarse-grained sandstone	Vaniklang	$9^0$18’18.8”N	$12^0$28’46.0”E

Table 2: Table showing conductivity of saturating water samples (σ_w), electrical resistivity for saturated samples (R_o), Resistivity of saturating water samples (R_w) and porosity (Ø)

Sample	**σ_w (mho)**	**R_w (Ωm)**	**R_o X10^3(Ωm)**	**Ø 0.20±0.01 (fraction)**
S_1	0.046	21.739	7.817± 0.198	0.22
S_2	0.044	22.727	7.890 ± 0.261	0.23
S_3	0.640	1.560	10.690±1.485	0.15
S_4	0.520	1.920	7.674±0.191	0.23
S_5	0.180	5.560	7.560±0.039	0.25
S_6	0.099	10.100	7.824±0.303	0.19
S_7	0.038	26.320	8.562±0.963	0.14
S_8	0.019	52.910	8.569±0.684	0.21
S_9	0.990	1.010	7.485±0.115	0.13
S_{10}	0.050	20.000	8.160±0.012	0.23
S_{11}	0.049	20.41	8.050±0.331	0.19
S_{12}	0.481	2.080	7.975±0.174	0.17
S_{13}	0.270	3.700	8.118±0.410	0.12
S_{14}	0.040	25.000	7.774±0.155	0.28

Table 3: Resistivity values (R_t) at various levels of time of water saturation for S_1.

Time (Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**R_t X10^3 (Ωm)**
3	1100.00	3.55 ± 0.03	3.099	8.263 ± 0.022
6	1100.00	3.55 ± 0.02	3.099	8.263 ± 0.022
9	1100.00	3.60 ± 0.03	3.o56	8.148 ± 0.023
12	1100.00	3.61 ± 0.01	3.047	8.125 ± 0.024
15	1100.00	3.62 ± 0.02	3.039	8.103 ± 0.024
18	1100.00	3.62 ± 0.02	3.039	8.103 ± 0.024
21	1100.00	3.64 ± 0.02	3.022	8.059 ± 0.025
24	1100.00	3.66 ± 0.02	3.005	8.015 ± 0.025
27	1100.00	3.69 ± 0.01	2.891	7.947 ± 0.025
30	1100.00	3.70 ± 0.00	2.973	7.928 ± 0.026
36	1100.00	3.72 ± 0.01	2.957	7.885 ± 0.026
39	1100.00	3.73 ± 0.02	2.949	7.864 ± 0.026
42	1100.00	3.80 ± 0.00	2.895	7.719 ± 0.028
45	1100.00	3.82 ± 0.04	2.880	7.679 ± 0.028
48	1100.00	385 ± 0.02	2.857	7.619 ± 0.029

Table 4: Resistivity values (R_t) at various levels of water saturation for S_2.

Time(Hrs)	**V (volts)**	**I (mA)**	**r_s X10^5 (Ω)**	**R_t X10^3 (Ωm)**
3	1100.00	3.00 ± 0.02	3.667	9.778 ± 0.327
6	1100.00	3.37 ± 0.02	3.264	8.704 ± 0.017
9	1100.00	3.38 ± 0.03	3.254	8.679 ± 0.017
12	1100.00	3.40 ± 0.00	3.235	8.620 ± 0.018
15	1100.00	3.49 ± 0.01	3.152	8.405 ± 0.261
18	1100.00	3.52 ± 0.02	3.125	8.333 ± 0.258
21	1100.00	3.55 ± 0.01	3.099	8.263 ± 0.022
24	1100.00	3.56 ± 0.02	3.080	8.240 ± 0.222
27	1100.00	3.57 ± 0.01	3.081	8.217 ± 0.023
30	1100.00	3.61 ± 0.01	3.047	8.126 ± 0.024
36	1100.00	3.65 ± 0.00	3.014	8.037 ± 0.025
39	1100.00	3.68 ± 0.02	2.989	7.971 ± 0.025
42	1100.00	3.80 ± 0.00	2.895	7.719 ± 0.028
45	1100.00	3.80 ± 0.00	2.895	7.719 ± 0.028
48	1100.00	3.80 ± 0.00	2.895	7.719 ± 0.028

Table 5: Resistivity values (R_t), at various levels of water saturation for S_3

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	1.08 ± 0.06	10.185	27.160 ± 1.714
6	1100.00	1.14 ± 0.06	9.649	25.731 ± 1.560
9	1100.00	2.13 ± 0.06	5.164	13.771 ± 0.554
12	1100.00	2.24 ± 0.02	4.911	13.096 ± 0.512
15	1100.00	2.27 ± 0.04	4.846	12.922 ± 0.501
18	1100.00	2.33 ± 0.01	4.721	12.589 ± 0.481
21	1100.00	2.41 ± 0.01	4.564	12.171 ± 0.456
24	1100.00	2.41 ± 0.02	4.564	12.171 ± 0.456
27	1100.00	2.56 ± 0.03	4.297	11.459 ± 0.416
30	1100.00	2.80 ± 0.08	3.929	10.447 ± 0.363
36	1100.00	2.88 ± 0.03	3.819	10.184 ± 0.348
39	1100.00	2.97 ± 0.02	3.704	9.877 ± 0.332
42	1100.00	3.02 ± 0.04	3.642	9.712 ± 0.323
45	1100.00	3.14 ± 0.18	3.503	9.341 ± 0.311
48	1100.00	3.19 ± 0.04	3.488	9.301 ± 0.298

Table 6: Resistivity values (R_t), at various levels of water saturation for S_4

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	2.66 ± 0.02	4.135	11.030 ± 0.392
6	1100.00	3.30 ± 0.00	3.056	8.148 ± 0.023
9	1100.00	3.63 ± 0.02	3.030	8.081 ± 0.024
12	1100.00	3.64 ± 0.02	3.022	8.059 ± 0.024
15	1100.00	3.65 ± 0.00	3.014	8.037 ± 0.025
18	1100.00	3.68 ± 0.01	2.989	7.971 ± 0.025
21	1100.00	3.69 ± 0.01	2.981	7.949 ± 0.241
24	1100.00	3.73 ± 0.01	2.949	7.864 ± 0.026
27	1100.00	3.75 ± 0.00	2.933	7.822 ± 0.027
30	1100.00	3.80 ± 0.00	2.895	7.719 ± 0.028
36	1100.00	3.80 ± 0.00	2.895	7.719 ± 0.028
39	1100.00	3.86 ± 0.02	2.850	7.599 ± 0.029
42	1100.00	3.87 ± 0.01	2.842	7.580 ± 0.225
45	1100.00	3.90 ± 0.00	2.821	7.521 ± 0.030
48	1100.00	3.92 ± 0.01	2.806	7.483 ± 0.030

Table 7: Resistivity values (R_t) at various levels of water saturation for S_5

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	3.68 ± 0.04	2989	8.148 ± 0.023
6	1100.00	3.76 ± 0.01	2.926	7.971 ± 0.025
9	1100.00	3.78 ± 0.04	2.910	7.801 ± 0.027
12	1100.00	3.79 ± 0.03	2.902	7.760 ± 0.232
15	1100.00	3.85 ± 0.02	2.857	7.740 ± 0.029
18	1100.00	3.86 ± 0.02	2.850	7.619 ± 0.029
21	1100.00	3.86 ± 0.02	2.850	7.619 ± 0.029
24	1100.00	3.86 ± 0.02	2.850	7.599 ± 0.226
27	1100.00	3.87 ± 0.01	2.842	7.599 ± 0.226
30	1100.00	3.87 ± 0.02	2.842	7.580 ± 0.029
36	1100.00	3.87 ± 0.02	2.842	7.580 ± 0.029
39	1100.00	3.88 ± 0.01	2.835	7.560 ± 0.224
42	1100.00	3.88 ± 0.01	2.835	7.560 ± 0.224
45	1100.00	3.89 ± 0.01	2.828	7.560 ± 0.029
48	1100.00	3.90 ± 0.00	2.821	7.560 ± 0.222

Table 8: Resistivity values (R_t) at various levels of water saturation for S_6

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	3.44 ± 0.02	3.197	8.527 ± 0.019
6	1100.00	3.46 ± 0.05	3.179	8.478 ± 0.019
9	1100.00	3.47 ± 0.02	3.170	8.453 ± 0.263
12	1100.00	3.59 ± 0.01	3.064	8.171 ± 0.251
15	1100.00	3.59 ± 0.03	3.064	8.171 ± 0.152
18	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
21	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
24	1100.00	3.61 ± 0.06	3.047	8.126 ± 0.249
27	1100.00	3.65 ± 0.02	3.014	8.037 ± 0.025
30	1100.00	3.87 ± 0.02	2.842	7.580 ± 0.231
36	1100.00	3.88 ± 0.02	2.835	7.560 ± 0.029
39	1100.00	3.88 ± 0.01	2.835	7.560 ± 0.029
42	1100.00	3.90 ± 0.00	2.821	7.521 ± 0.030
45	1100.00	3.90 ± 0.00	2.821	7.521 ± 0.030
48	1100.00	3.90 ± 0.00	2.821	7.521 ± 0.030

Table 9: Resistivity values (R_t) at various levels of water saturation for S_7

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	2.36 ± 0.01	4.661	12.430 ± 0.472
6	1100.00	2.53 ± 0.03	4.348	11.590 ± 0.421
9	1100.00	2.66 ± 0.05	4.151	11.070 ± 0.394
12	1100.00	2.87 ± 0.03	3.056	10.220 ± 0.349
15	1100.00	3.03 ± 0.01	3.630	9.68 ± 0.322
18	1100.00	3.06 ± 0.02	3.595	9.586 ± 0.317
21	1100.00	3.08 ± 0.01	3.571	9.524 ± 0.314
24	1100.00	3.08 ± 0.04	3.571	9.524 ± 0.314
27	1100.00	3.14 ± 0.02	3.503	9.342 ± 0.305
30	1100.00	3.19 ± 0.01	3.448	9.195 ± 0.298
36	1100.00	3.22 ± 0.03	3.462	9.110 ± 0.294
39	1100.00	3.50 ± 0.04	3.143	8.381 ± 0.021
42	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
45	1100.00	3.73 ± 0.02	2.946	7.864 ± 0.026
48	1100.00	3.86 ± 0.02	2.821	7.599 ± 0.029

Table 10: Resistivity values (R_t) at various levels of water saturation for S_8

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	2.80 ± 0.03	3.929	10.480 ± 0.363
6	1100.00	3.02 ± 0.02	3.642	9.713 ± 0.324
9	1100.00	3.05 ± 0.02	3.607	9.618 ± 0.319
12	1100.00	3.10 ± 0.02	3.548	9.462 ± 0.310
15	1100.00	3.15 ± 0.01	3.492	9.312 ± 0.304
18	1100.00	3.15 ± 0.02	3.492	9.312 ± 0.304
21	1100.00	3.16 ± 0.02	3.481	9.283 ± 0.302
24	1100.00	3.17 ± 0.05	3.470	9.253 ± 0.301
27	1100.00	3.30 ± 0.00	3.303	8.809 ± 0.281
30	1100.00	3.39 ± 0.01	3.245	8.653 ± 0.017
36	1100.00	3.39 ± 0.01	3.245	8.653 ± 0.017
39	1100.00	3.45 ± 0.02	3.188	8.502 ± 0.019
42	1100.00	3.56 ± 0.04	3.090	8.240 ± 0.023
45	1100.00	3.57 ± 0.02	3.081	8.217 ± 0.023
48	1100.00	3.72 ± 0.02	2.957	7.885 ± 0.029

Table 11: Resistivity values (R_t) at various levels of water saturation S_9

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	3.65 ± 0.00	3.014	8.037 ± 0.025
6	1100.00	3.68 ± 0.02	2.989	7.971 ± 0.025
9	1100.00	3.74 ± 0.01	2.941	7.843 ± 0.022
12	1100.00	3.74 ± 0.02	2.941	7.843 ± 0.027
15	1100.00	3.78 ± 0.01	2.910	7.760 ± 0.232
18	1100.00	3.84 ± 0.03	2.865	7.639 ± 0.028
21	1100.00	3.85 ± 0.02	2.857	7.616 ± 0.029
24	1100.00	3.86 ± 0.02	2.850	7.599 ± 0.029
27	1100.00	3.86 ± 0.02	2.850	7.599 ± 0.030
30	1100.00	3.89 ± 0.03	2.828	7.541 ± 0.031
36	1100.00	3.90 ± 0.00	2.821	7.521 ± 0.031
39	1100.00	3.90 ± 0.00	2.821	7.521 ± 0.031
42	1100.00	3.90 ± 0.01	2.821	7.521 ± 0.030
45	1100.00	3.92 ± 0.01	2.806	7.483 ± 0.030
48	1100.00	3.98 ± 0.01	2.764	7.370 ± 0.031

Table 12: Resistivity values (R_t) at various levels of water saturation for S_{10}

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	3.50 ± 0.00	3.143	8.381 ± 0.021
6	1100.00	3.50 ± 0.00	3.143	8.381 ± 0.021
9	1100.00	3.52 ± 0.01	3.125	8.333 ± 0.258
12	1100.00	3.56 ± 0.02	3.080	8.240 ± 0.022
15	1100.00	3.57 ± 0.02	3.081	8.217 ± 0.023
18	1100.00	3.58 ± 0.01	3.073	8.194 ± 0.023
21	1100.00	3.58 ± 0.01	3.073	8.194 ± 0.023
24	1100.00	3.59 ± 0.01	3.064	8.171 ± 0.025
27	1100.00	3.59 ± 0.01	3.064	8.171 ± 0.025
30	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
36	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
39	1100.00	3.60± 0.00	3.056	8.148 ± 0.023
42	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
45	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
48	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023

Table 13: Resistivity values (R_t) at various levels of water saturation for S_{11}

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	3.22 ± 0.01	3.462	9.110 ± 0.294
6	1100.00	3.32 ± 0.04	3.313	8.835 ± 0.015
9	1100.00	3.34 ± 0.02	3.293	8.782 ± 0.016
12	1100.00	3.41 ± 0.01	3.226	8.602 ± 0.018
15	1100.00	3.42 ± 0.01	3.216	8.577 ± 0.018
18	1100.00	3.42 ± 0.02	3.216	8.577 ± 0.018
21	1100.00	3.49 ± 0.01	3.152	8.405 ± 0.020
24	1100.00	3.50 ± 0.00	3.143	8.381 ± 0.021
27	1100.00	3.50 ± 0.00	3.143	8.381 ± 0.021
30	1100.00	3.64 ± 0.01	3.022	8.059 ± 0.024
36	1100.00	3.77 ± 0.01	2.918	7.781 ± 0.027
39	1100.00	3.78 ± 0.01	2.910	7.760 ± 0.232
42	1100.00	3.78 ± 0.02	2.910	7.760 ± 0.232
45	1100.00	3.79 ± 0.01	2.902	7.740 ± 0.029
48	1100.00	3.80 ± 0.02	2.895	7.719 ± 0.028

Table 14: Resistivity values (R_t) at various levels of water saturation for S_{12}

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X10^3 (Ωm)
3	1100.00	3.52 ± 0.04	3.125	8.333 ± 0.021
6	1100.00	3.56 ± 0.01	3.090	8.240 ± 0.022
9	1100.00	3.58 ± 0.01	3.073	8.194 ± 0.023
12	1100.00	3.58 ± 0.01	3.073	8.194 ± 0.023
15	1100.00	3.59 ± 0.01	3.064	8.171 ± 0.251
18	1100.00	3.59 ± 0.01	3.064	8.171 ± 0.251
21	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
24	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
27	1100.00	3.63 ± 0.01	3.030	8.081 ± 0.024
30	1100.00	3.65 ± 0.00	3.014	8.037 ± 0.025
36	1100.00	3.67 ± 0.01	2.997	7.993 ± 0.025
39	1100.00	3.69 ± 0.03	2.981	7.949 ± 0.025
42	1100.00	3.74 ± 0.01	2.941	7.843 ± 0.026
45	1100.00	3.75 ± 0.03	2.933	7.822 ± 0.027
48	1100.00	3.76 ± 0.01	2.926	7.801 ± 0.027

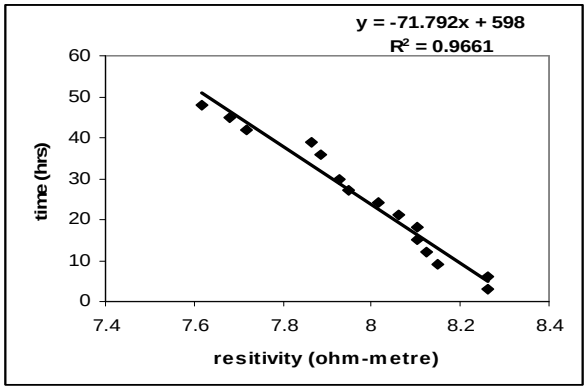
Table 15: Resistivity values (R_t) sat various levels of water saturation for S_{13}

Time (Hrs)	V (volts)	I (mA)	r_s X10^5 (Ω)	R_t X 10^3 (Ωm)
3	1100.00	2.63 ± 0.01	4.183	11.150 ± 0.399
6	1100.00	2.75 ± 0.04	4.000	10.670 ± 0.373
9	1100.00	2.92 ± 0.03	3.767	10.050 ± 0.340
12	1100.00	3.01 ± 0.04	3.655	9.745 ± 0.325
15	1100.00	3.13 ± 0.04	3.514	9.372 ± 0.307
18	1100.00	3.20 ± 0.00	3.438	9.167 ± 0.297
21	1100.00	3.42 ± 0.01	3.216	8.557 ± 0.018
24	1100.00	3.46 ± 0.03	3.179	8.478 ± 0.020
27	1100.00	3.55 ± 0.02	3.099	8.263 ± 0.022
30	1100.00	3.60 ± 0.02	3.056	8.148 ± 0.023
36	1100.00	3.63 ± 0.02	3.030	8.081 ± 0.024
39	1100.00	3.66 ± 0.02	3.006	8.015 ± 0.025
42	1100.00	3.66 ± 0.02	3.006	8.015 ± 0.025
45	1100.00	3.82 ± 0.02	2.880	7.679 ± 0.028
48	1100.00	3.83 ± 0.01	2.872	7.659 ± 0.028

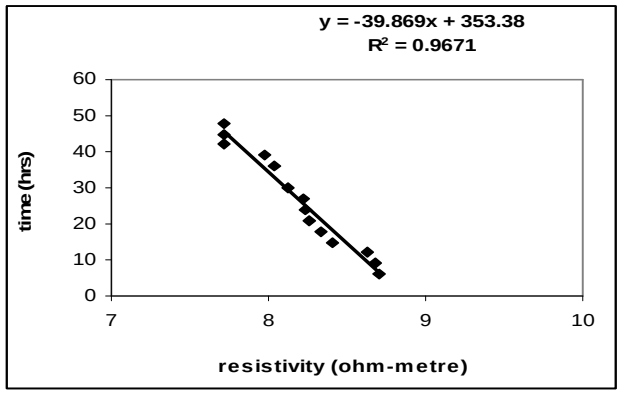
Table 16: Resistivity values (R_t) at various levels of water saturation for S_{14}

Time (Hrs)	V (volts)	I (mA)	r_s X 10^5 (Ω)	R_t X 10^3 (Ωm)
3	1100.00	3.48 ± 0.01	3.161	8.426 ± 0.261
6	1100.00	3.54 ± 0.02	3.107	8.286 ± 0.022
9	1100.00	3.56 ± 0.02	3.090	8.240 ± 0.022
12	1100.00	3.60 ± 0.00	3.056	8.148 ± 0.023
15	1100.00	3.64 ± 0.02	3.022	8.050 ± 0.024
18	1100.00	3.68 ± 0.04	2.989	7.971 ± 0.025
21	1100.00	3.69 ± 0.01	2.981	7.949 ± 0.025
24	1100.00	3.70 ± 0.00	2.973	7.928 ± 0.026
27	1100.00	3.73 ± 0.00	2.949	7.864 ± 0.026
30	1100.00	3.75 ± 0.02	2.933	7.822 ± 0.027
36	1100.00	3.77 ± 0.03	2.918	7.781 ± 0.027
39	1100.00	3.78 ± 0.01	2.910	7.760 ± 0.232
42	1100.00	3.82 ± 0.02	2.880	7.679 ± 0.028
45	1100.00	3.83 ± 0.01	2.872	7.659 ± 0.028
48	1100.00	3.85 ± 0.02	2.857	7.619 ± 0.029

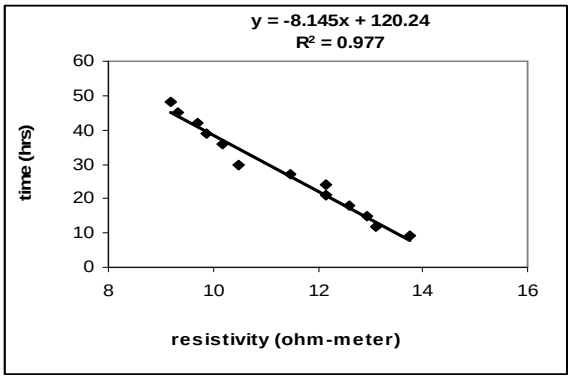
Investigation of the effect of time of saturation on resistivity showed that resistivity decreases with increase in time of saturation for some selected samples studied. This is as would be expected since more water fills the pore spaces with time thus, providing conductive pathways for electrical current. This observation is clearly seen in Figures 2 to 4 which showed plots of resistivity against time of saturation.



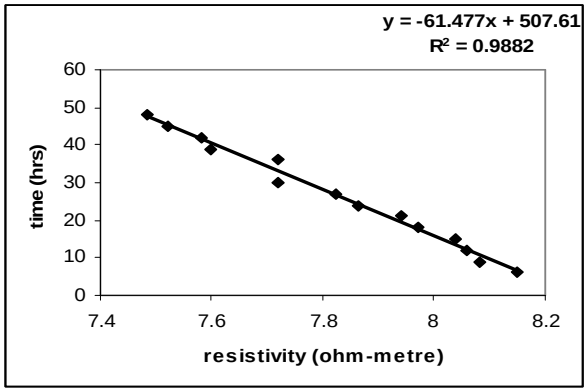
a.



b.

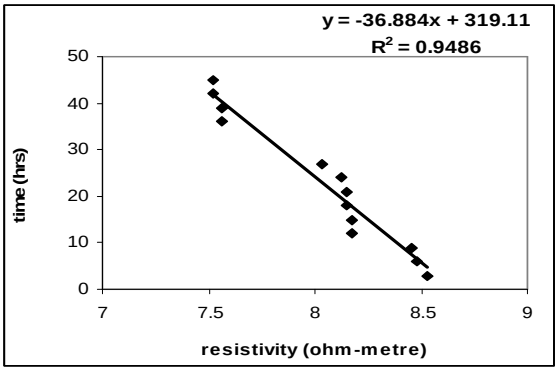


c.

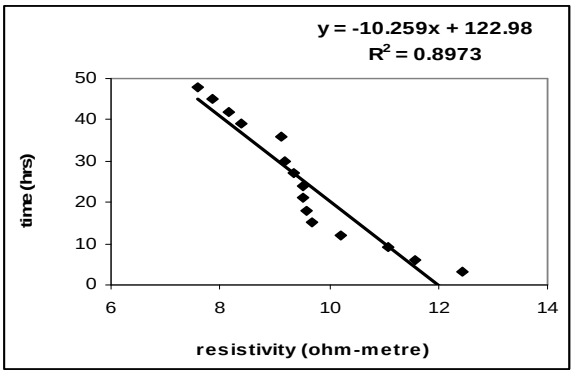


d.

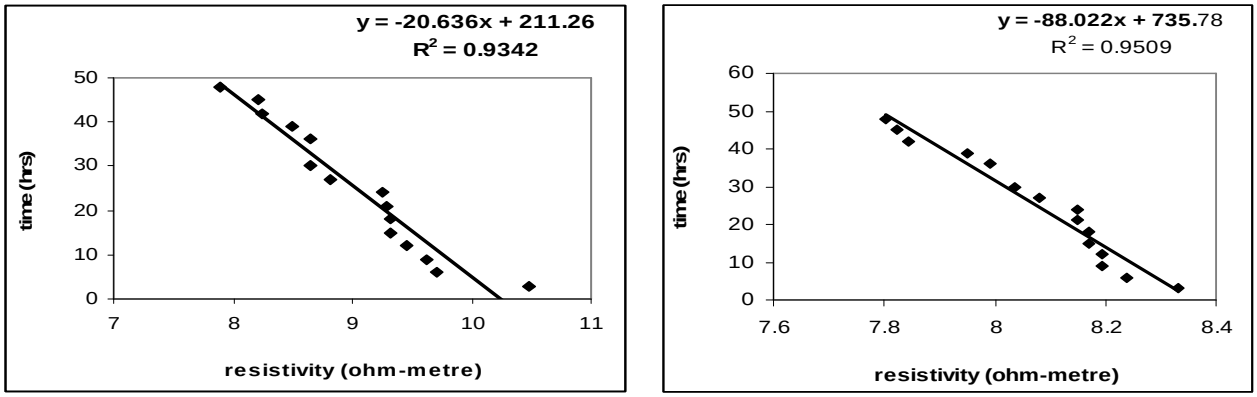
Figure 2: Variation of resistivity x10^3Ωm with time of saturation for sample S_1 (a), sample S_2 (b), Sample S_3 (c) and Sample S_4 (d).



a

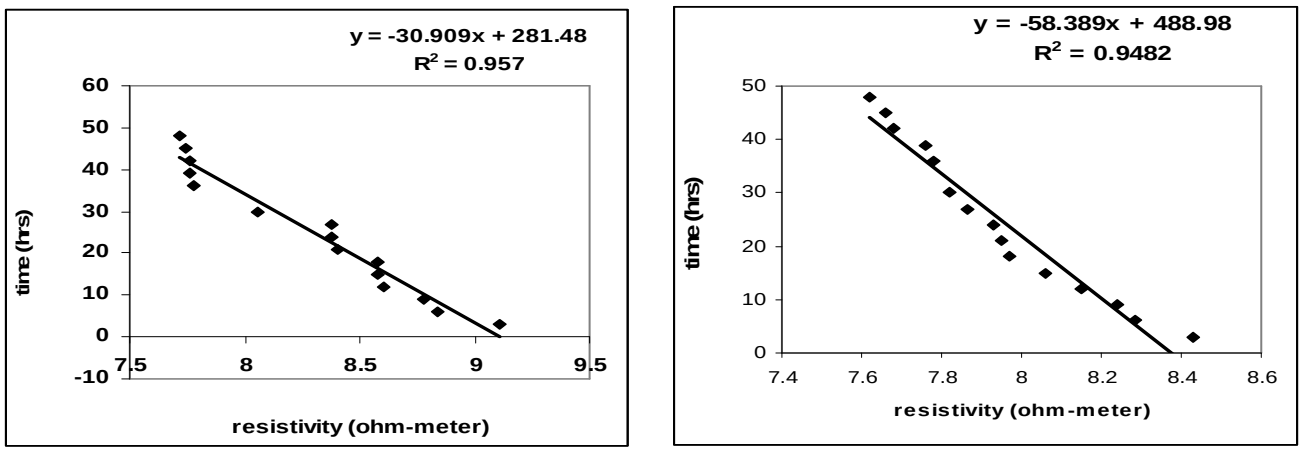


b



c d

Figure 3: Variation of resistivity x10^3Ωm with time of water saturation for sample S_6 (a), Sample S_7 (b), sample S_8 (C), and sample S_9 (d).



a b

Figure 4: Variation of resistivity x10^3Ωm with time of saturation for sample S_{12} (a), sample S_{14} (b).

Generally, the plots showed good correlation between both quantities with correlation coefficient R^2 ranging from 0.8973 to 0.9882.

Table 17 shows electrical resistivity anisotropy values for the eleven rock samples investigated. Results showed that the rocks exhibit low anisotropy with values from 1.2:1 to 1.7:1. The anisotropy of the electrical resistivity in natural rocks is caused by the preferred orientation of conducting minerals or accessories (for example graphite, ores); the orientation of the grains, the preferred orientation of the wet or water saturated pores or cracks, and fine layering of rock components with different conductivity (clay-sand sandwich layering) [6]. The low anisotropy indicates that there is almost uniform orientation of the conducting minerals and water wet pores. The highest anisotropy values were exhibited by samples S_1, S_8, S_{12} and S_{14}. Samples S_8, S_{12} and S_{14} are coarse-grained sandstones; hence the possibility that there may be varying orientation of the conducting minerals and the water saturated pores. The reason of the high anisotropy value of S_1 being a fine-grained sandstones is yet unknown, though there may be variations in the orientation of the pores and minerals. The lowest anisotropy value was exhibited by sample S_3. Although a coarse-grained sandstone, there is possibility of uniform orientation of the grains.

The low anisotropy also indicates that the rocks are highly saturated with water; hence there is a slight variation in anisotropy. Pronounced electrical anisotropy in porous media usually implies presence of hydrocarbon.

Table 17: Results of electrical anisotropy measurements

Sample	**Mean R_o (x 10^3 Ωm)**			**Anisotropy λ**
	α	**β**	**γ**	
S_1	7.817 ± 0.198	4.714 ± 0.000	4.588 ± 0.223	1.7:1
S_2	7.980 ± 0.261	5.519 ± 0.019	6.837 ± 0.429	1.5:1

S_3	10.690 ± 1.435	9.137 ± 2.622	10.298 ± 2.694	1.2:1
S_6	7.824 ± 0.303	4.941 ± 0.054	5.286 ± 0.178	1.6:1
S_7	8.562 ± 0.963	5.393 ± 0.018	6.410 ± 0.063	1.6:1
S_8	8.569 ± 0.684	5.202 ± 0.488	6.112 ± 0.046	1.7:1
S_9	7.485 ± 0.115	4.912 ± 0.681	5.222 ± 0.028	1.5:1
S_{11}	8.050 ± 0.331	5.143 ± 0.145	5.080 ± 0.110	1.6:1
S_{12}	7.975 ± 0.174	4.668 ± 0.046	4.603 ± 0.020	1.7:1
S_{13}	8.118 ± 0.410	5.881 ± 0.230	6.097 ± 0.504	1.4:1
S_{14}	7.774 ± 0.155	4.683 ± 0.318	4.833 ± 0.491	1.7:1

Conclusion

The electrical resistivity of rocks depends on the physical properties of rocks and the fluid it contains. In porous media or rocks bearing water, conductivity is controlled by ionic/electrolytic conductivity and surface conductivity. The resistivity of the saturated samples was found to have an average value of $8.160 \pm 0.229 \times 10^3$ Ωm, showing that the resistivity of the rocks depends largely on the saturating fluid than the minerals that formed the rock matrix.

The rocks displayed low values of electrical resistivity anisotropy ranging from 1.2: 1 to 1.7: 1, indicating that the rocks grains are uniformly oriented.

Investigation of the effect of time of water saturation on resistivity showed that the samples resistivity decreases with increase in time of saturation.

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