INVESTIGATING ELECTRICAL RESPONSE TO WATER SATURATION OF AGBADA SANDSTONE IN AN X-FIELD NIGER DELTA, NIGERIA.

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ABSTRACT

In an attempt to characterize a reservoir in a field, importance is given to living models as it serves critical function in estimating if the reservoir under study is economically viable. Having a good knowledge of electrical response to reservoir rocks is important in characterizing and modeling the behavior of fluids at the subsurface. In this study, core plugs extracted from core barrels in a Niger Delta oil field were analyzed in the laboratory in order to determine the electrical properties of the samples and their relationship with each other and formation fluid. This was achieved by using a brine of a known concentration for simulation of core plugs. Results obtained show that for the unconsolidated sandstone, Formation resistivity factor increases with increase in confining pressure. This characteristic depends on the porosity of the Formation and type of fluid present. Resistivity values in a reservoir will increase with increase in capillary pressure and decrease with water saturation. Decrease in cementation exponent increases the rate of permeability in reservoir sand. However, resistivity values decrease with clay presence in reservoir sand.

Keywords: Core plug, reservoir, resistivity, water saturation

1 INTRODUCTION

Once an exploration well has been drilled, the "living model" begins to serve more critical function, determining whether or not the well is a commercial success and defining the initial characterization of the reservoir. Model studies in geophysics have become a very important tool in the interpretation of geophysical and electrical data. Electrical modelling studies involve the generation of electrical response over regular objects which are buried in a medium with contrasting physical properties. The use of models in electrical method of exploration such as electrical resistivity is a useful aid in the interpretation of electrical responses within a medium in different fields [1]. Electrical resistivity measurements are commonly used to investigate fluid saturations in multiphase flow system [2]. For a critical reservoir parameter determination, it is best to characterize the property of a rock type. The rising interest in understanding some basic properties of reservoir rocks such as electrical properties has led to the extraction of more data from the earth subsurface [3].

A core is usually the most reliable piece of information. It is a direct physical sample of the formation in which a continuous cylindrical sample of the Formation is recovered and it provides geologist with the only record of real subsurface lithology. Analysis, results and models obtained from representative reservoir rocks (specimen) from the subsurface in an area can produce key information that can lead to effective description, exploration and exploitation. Study of these basic parameters gives an insight into reservoir performance and establishment of a sound basis for reservoir estimation and exploitation. This is achieved in this study through quantitative analysis of parameters generated via empirical model on core samples from laboratory.

The potential and performance of reservoir sand depend on certain characteristics and properties which include porosity, permeability, grain size and grain shape, degree of compaction, amount of matrix and cement component. Electrical resistivity response as observed in a Formation is that property that usually describes the ability of a representative material of the medium to support the movement of positive and negative ions.

In a Formation, values of resistivity (R) measured are usually directly proportional to those of its fluid resistivity (Rw) and found to be inversely proportional to the product of the water saturation (Sw) and the porosity (Ø) of that Formation. These resistivity values fall within the range of 0.2 to 1000 Ωm. Values higher than 1000 Ωm are not usually found in Formations that are permeable [4]. Recent studies have shown that only a few model studies investigate the relationship between electrical properties and the geometrical structure of a porous medium as attention has been on the effect of water concentration in a medium. Electrical and petrophysical properties of the various medium have also received less attention in the past [5, 6, 7, 8].

Most Formations when dry do not conduct electric current when logged for oil and gas. This is because the current tends to flow through the interstitial water which is made conductive by salt in solution if present. These salts when present, however, dissociate into cations and anions which have the tendency of moving from point to point carrying electric current through the solution under the influence of an electric filed. High salt in solution leads to a low resistivity (high conductivity) value for a particular Formation. However, the amount of shale present in a Formation contributes to Formation conductivity. Conduction in a medium is an exchange process whereby (usually the cation) moves under the influence of the impressed electric field between exchange sites on the surface of the clay particles. Results obtained from most Formation logged indicate that the net effect of shaliness is dependent on the amount present, its type and distribution and on the nature of the relative amount of the Formation water.

2 MATERIALS AND METHODS

2.1 Geology of the study Area

The Niger Delta is perhaps the most important sedimentary basin in Sub-Sahara Africa with respect to petroleum products. It is a pro-grading depositional complex within the Cenozoic Formation of the Southern Nigeria and located between latitude 4^0 and 7^0N, longitude 5^0 and 9^0E (Figure 1) covering an area of about 75000 km^2 [9]. Authors of [10] described the Basin as having resulted from the third phase of the three major tectono-depositional cycles undergone by the Nigerian South-Eastern basins. The cycle which was the third began at the end of the Eocene and was marked by erosion and/or non-deposition [11].

Sandstones are the most common reservoir rocks in the Niger Delta. Over 80% of the clastic grains are quartz. By the usual assumptions made on the conditions of depositions of sandstones, they are expected to be very porous and permeable. Porosity determinations in Niger Delta show that values range from 15- 40% in the reservoir rocks because they are not well consolidated. Permeability values vary widely but hardly exceed a maximum of 10 Darcies [12,13].

The known onshore and near shore tertiary reservoir of the Niger Delta Basin are all units of the Agbada Formation. Due to the high sedimentation rate of this Formation, the sands are under compacted, with high porosity and permeability and generally good. Petroleum in Niger Delta is produced from sandstones and unconsolidated sands predominantly in the Agbada Formation. Characteristics of the reservoirs in the Agbada are controlled by depositional environment and by depth of burial [14]. Based on reservoir geometry and quality, the most important reservoir type are point bars of distributary channels and coastal barrier bars intermittently cut by sand-filled channel. Authors of [15] described the reservoir as having porosity of 40%, 2 Darcies permeability and a thickness of 100 meters. Porosity only decreases with depth because of the young age of the sediment and the coolness of the delta complex. In the outer portion of the delta complex, deep-sea channel sands, low-stand sand bodies and proximal turbidities create potential reservoirs [16].

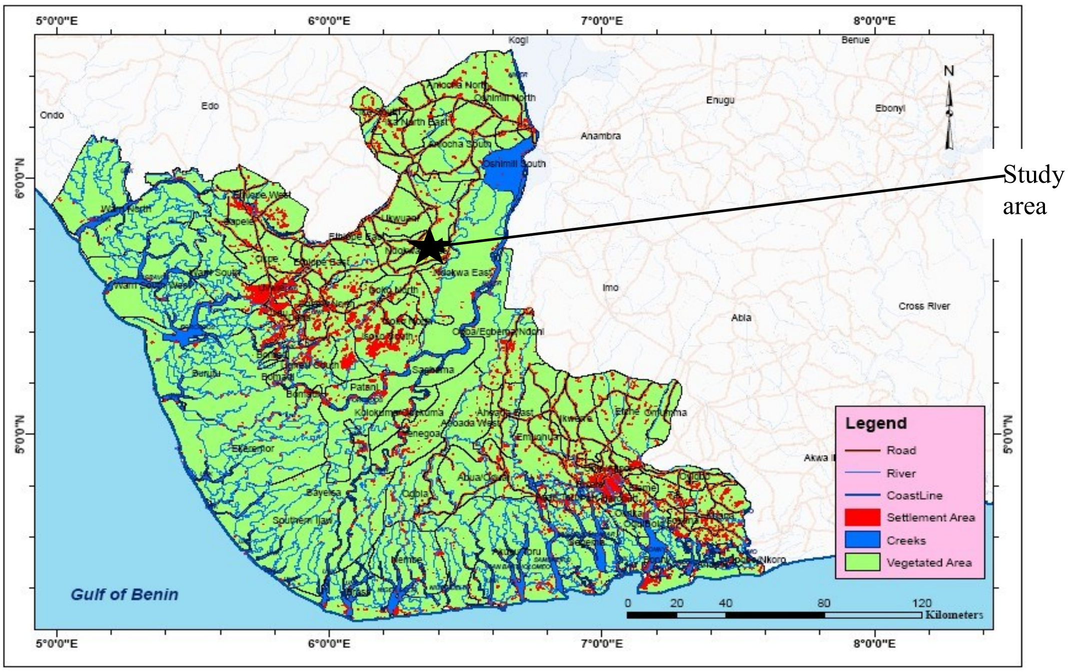

Figure 1. Map of Niger Delta showing the study area

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2.2 Study design

The materials used for this study were core plugs extracted from core barrels from one of the fields in the study area (Figure 2). The field has five wells drilled into the structure. Samples used were extracted from well five over a thickness of 27.75 m that was cored for the analysis. Table 1 shows the lithological description of the drilled well from which core plugs were extracted. The core plugs used were oven dried and saturated with a brine of synthetic concentration of 44000 ppm and resistance of 0.143 Ωm to serve as the in-situ water of saturation at 100 % for the simulation test. Studies have shown that the resistivity of a clean Formation (i.e. one containing no appreciable amount of clay) is proportional to the resistivity of the brine with which it is fully saturated, as the higher the concentration of the brine, the less the resistivity values obtained. The constant of proportionality is called the Formation Resistivity Factor "FF".

Figure 2. Core plugs/ barrels of rock sample used for the laboratory analysis

Core analysis provides direct point measurement of some of the basic rock properties which are needed to determine the fluid content, distribution and flow behavior of reservoir fluid or injection fluid. Core plugs were taken as close to two-foot spacing as possible without any regard for variations in lithology. The aim of this simple selection is to ensure that data are measured on the most representative samples where the degree of heterogeneity will be minimized or at least the degree of heterogeneity can be quantified. A total of seventeen core plugs (Figure 2, Table 1) were extracted and used for routine analysis. Next, six samples (samples 1, 4, 9, 11, 14 and 16) were labelled as samples A, B, C, D, E and F (Tables 2-7) and used for the electrical resistivity test.

Table 1. Lithological description for seventeen core samples extracted from the well

Sample number	Depth (meter)	Horizontal permeability Kair (mD) @2900 psig	Lithological Description
01	2526.25	3110	Sandstone, fine-medium grain, poorly cemented
02	2528.71	3520	Sandstone, fine-medium grain, poorly cemented
03	2529.28	2690	Sandstone, fine-medium grain, poorly cemented
04	2532.76	304	Sandstone, fine-medium grain, rare mud drapes
05	2533.27	938	Sandstone, fine-medium grain, rare mud drapes
06	2534.77	1940	Sandstone, fine-medium grain, poorly cemented
07	2536.34	2180	Sandstone, fine-medium grain, weakly laminated
08	2539.75	1250	Sandstone, fine-medium grain, weakly laminated
09	2540.28	2530	Sandstone, fine-medium grain, weakly laminated
10	2542.00	1190	Sandstone, fine-medium grain, weakly laminated
11	2543.52	2560	Sandstone, fine-medium grain, weakly laminated
12	2545.05	1520	Sandstone, fine-medium grain, weakly laminated
13	2546.64	2080	Sandstone, fine-medium grain, ripple laminated
14	2548.28	2300	Sandstone, fine-medium grain, ripple laminated
15	2550.33	2690	Sandstone, fine-medium grain, ripple laminated
16	2552.79	4930	Sandstone, fine-medium grain, weakly laminated
17	2554.00	2370	Sandstone, fine-medium grain, weakly laminated

2.3 Core cleaning and plug drying

Core cleaning was accomplished by means of hot solvents extraction (Soxhlett) techniques in which Toluene and Methanol were used to clean the samples of oil, water, and salt. This was done below the boiling point of water to avoid the removal of water before the oil. Two basic methods were used to achieve this, the batch cleaning and the Dean – Stark method. Samples were loaded in Soxhlett after pressuring them up to 400 psi and then batch cleaned in Toluene which was heated to a temperature below the boiling point of water (<100°C) to

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distil the oil present in the samples until Toluene was clean. Samples were then examined for evidence of staining and fluorescence. The presence of salt was tested by the use of Silver Trioxonitrate V ($AgNO_3$). The samples were then weighed at the end of the cleaning process to determine weight difference before and after cleaning. Drying was achieved using the conventional oven for a minimum of 24 hours and cooling to room temperature in a desiccator with samples in a metal tray. Checking was repeated at 8 hours' intervals until constant weights were achieved. Samples were considered to be at a constant weight when weights were repeated to plus or minus 0.01 grams for plug samples.

2.4 Brine preparation/storage and resistivity measurement

440 g of NaCl were dissolved in 10 liters of distilled water for the preparation of the brine and was built in part per million (ppm). Electrical resistivity of brine is used as a check on the total salinity of the brine and also the value is required to determine the core resistivity properties. Evacuation was carried out to remove dissolved air in the brine by boiling at room condition at pressure approaching vacuum and stirring. The GenRad Digibridge was used for brine resistivity determination. The brine resistivity was calculated by multiplying the resistance reading (in ohms) by the resistivity cell constant 0.002 and converted to the equivalent value at the standard temperature of 77°F (25°C) using Arp's equation.

$$\text{Brine resistivity} = \text{resistance} \times 0.002\ (\text{temperature reading} + 6.77) / 83.77 \qquad (1)$$

where

Temperature reading = temperature reading on the Digibridge; 6.77 and 83.77 are constant values.

Inserting the measured resistance and temperature values into equation 1, the Brine resistivity calculated = 0.143 ohms.

2.5 Electrical properties measurement

Capillary Pressure, Porous Plate Method (Air-Brine) System

To measure core resistivity at ambient and at stress conditions, the samples were first de-saturated with air using an evacuation pump for 12 hours (overnight). The samples were then saturated with the prepared brine of a known concentration (samples were weighed after de-saturation and saturation with brine) for minimum of 8 hours and stored in a saturant bath. Archimedes BV, GV and saturated VP were determined and recorded, the following parameters were then determined at ambient and stressed pressure condition: Formation Factor (FF), Cementation Factor (m), Resistivity Index (RI), Saturation Exponent (n) and Capillary Pressure (PC), VS Water saturation (Sw). The samples were loaded into the Hydrostatic core holder as shown in Figure 3.

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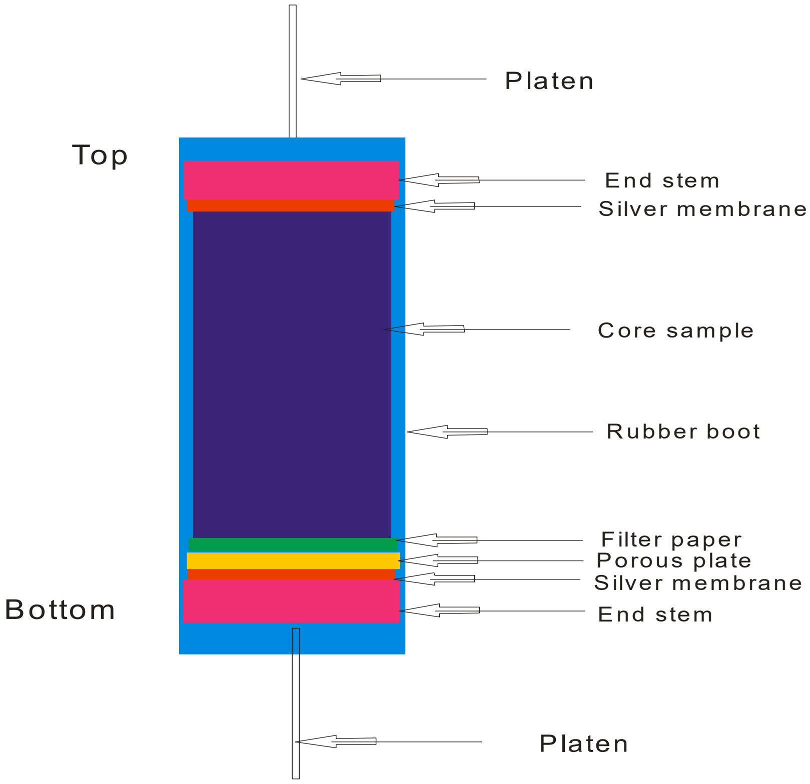

Figure 3. Arrangement of a core plug in the hydrostatic core holder

3 RESULTS AND DISCUSSION

Formation factor represented as $1/Ø^m$ [17] is sometimes modified to $a/Ø^m$, 'a' is a constant meant to correct for Formation parameters such as variation in compaction, pore structure and grain size. The constant is sometimes denoted as tortuosity factor or cementation intercept, with values ranging between 0.6 and 1. The core plugs extracted from the samples of the study field show a slightly consolidated sands and going by Humble's formula for unconsolidated sandstones, $F=0.62/Ø^{2.15}$. As observed from the results of the various plugs (Tables 2-7), Formation resistivity factor increases with an increase in confining pressure from 500-2900 psi; for all plugs as fluid content is lost due to increasing pressure. Formation factor is a fundamental measurement for reservoirs fluid saturation, which is a function of porosity, type of fluid (i.e. hydrocarbon, salt or fresh water) and type of rock. This was measured as a ratio of the Formation resistivity and brine resistivity (Ro/Rw). Results also show that the value of FF reduces as brine resistivity rises and the size of sand grain decreases.

Table 2. Electrical Properties Measurement in Conjunction with Porous Plate Capillary Pressure - Synthetic formation Brine concentration = 44000ppm

Sample Number	Confining Pressure (psi)	Permeability (mD)	Porosity (fraction)	Formation Resistivity Factor (FF)	Water Sat. Sw (fraction)	Formation Resistivity Index (RI)	Cementation Exponent (m)
A	500	3110	0.337	5.03	1.000	-	-1.49
	2900		0.314	6.05	1.000	1.00	-1.56
					0.981	1.03	
					0.567	4.44	
					0.437	12.28	
					0.418	14.88	
					0.402	19.22	
					0.395	21.49	

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Table 3. Electrical Properties Measurement in Conjunction with Porous Plate Capillary Pressure - Synthetic formation Brine concentration = 44000ppm

Sample Number	Confining Pressure (psi)	Permeability (mD)	Porosity (fraction)	Formation Resistivity Factor (FF)	Water Sat. Sw (fraction)	Formation Resistivity Index (RI)	Cementation Exponent (m)
B	500	304	0.291	10.45	1.000	-	-1.90
	2900		0.276	11.71	1.000	1.00	-1.91
					0.965	1.02	
					0.705	1.88	
					0.572	3.29	
					0.484	4.51	
					0.465	5.10	
					0.471	5.19	

Table 4. Electrical Properties Measurement in Conjunction with Porous Plate Capillary Pressure - Synthetic formation Brine concentration = 44000ppm

Sample Number	Confining Pressure (psi)	Permeability (mD)	Porosity (fraction)	Formation Resistivity Factor (FF)	Water Sat. Sw (fraction)	Formation Resistivity Index (RI)	Cementation Exponent (m)
C	500	2530	0.344	5.78	1.000	-	-1.64
	2900		0.337	6.46	1.000	1.00	-1.71
					0.968	1.02	
					0.192	37.09	
					0.114	102.85	
					0.089	151.83	
					0.086	182.87	
					0.078	203.56	

Table 5. Electrical Properties Measurement in Conjunction with Porous Plate Capillary Pressure - Synthetic formation Brine concentration = 44000ppm

Sample Number	Confining Pressure (psi)	Permeability (mD)	Porosity (fraction)	Formation Resistivity Factor (FF)	Water Sat. Sw (fraction)	Formation Resistivity Index (RI)	Cementation Exponent (m)
D	500	4930	0.381	5.89	1.000	-	-1.84
	2900		0.390	7.30	1.000	1.00	1.94
					0.957	1.10	
					0.672	3.37	
					0.351	66.82	
					0.272	89.00	
					0.267	108.99	
					0.259	119.97	

Table 6. Electrical Properties Measurement in Conjunction with Porous Plate Capillary Pressure - Synthetic formation Brine concentration = 44000ppm.

Sample Number	Confining Pressure (psi)	Permeability (mD)	Porosity (fraction)	Formation Resistivity Factor (FF)	Water Sat. Sw (fraction)	Formation Resistivity Index (RI)	Cementation Exponent (m)

E	500	3330	0.348	5.76	1.000	-	-1.66
	2900		0.333	6.22	1.000	1.00	-1.66
					0.978	1.03	
					0.567	2.73	
					0.130	48.29	
					0.057	171.28	
					0.047	203.64	
					0.042	235.37	

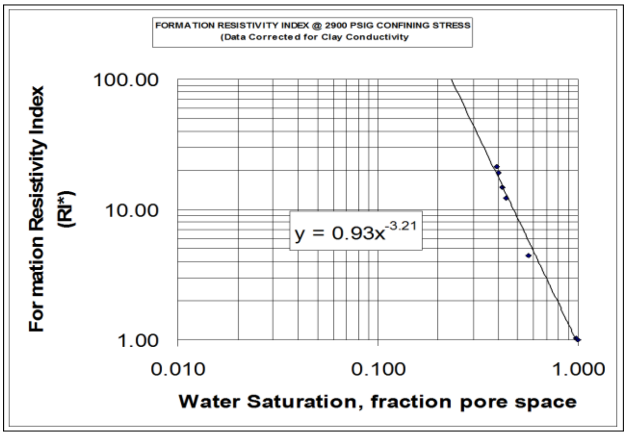
Table 7. Electrical Properties Measurement in Conjunction with Porous Plate Capillary Pressure - Synthetic formation Brine concentration = 44000ppm

Sample Number	Confining Pressure (psi)	Permeability (mD)	Porosity (fraction)	Formation Resistivity Factor (FF)	Water Sat. Sw (fraction)	Formation Resistivity Index (RI)	Cementation Exponent (m)
F	500	2560	0.359	5.38	1.000	-	-1.64
	2900		0.341	6.71	1.000	0.00	-1.77
					0.952	0.00	
					0.448	3.99	
					0.209	27.17	
					0.108	80.98	
					0.093	95.25	
					0.084	118.41	

Cementation exponent (m) measured is a physical parameter in a Formation that shows how the pore network in a porous medium increases the resistivity of the medium. It is often related to the permeability of the medium. From the results obtained as shown in the Tables, permeability values increase with a decrease in cementation exponent. With an increase in confining pressure from 500-2900 psi, the permeability of the samples decreases thereby increasing the cementation exponent. A reduction in the magnitude and connectivity of permeability in a Formation containing hydrocarbon could reduce the level of production. Increasing pressure also decreases the pore volume and porosity of the core plugs, hence of the Formation. This parameter, for unconsolidated sandstones has been found to be near 1.3 while for consolidated sandstones are $1.8<m<2.0$. The value 'm' is assumed usually not too dependent on temperature. From the laboratory analysis carried out on the core plugs, cementation values ranges from 1.41-1.91 indicating a slightly consolidated formation for the study field. These values decrease with increase in permeability and porosity across the samples.

Saturation exponent (n), another parameter that models the dependence on the non-conductive fluid (such as hydrocarbons), that is present in a Formation has values close to 2. The presence of oil-wet rock in a Formation indicate discontinuous droplet of water within the pore spaces which usually leads to rocks becoming less conductive, while a water-wet rock will maintain continuous film along the pore walls leading to the Formation rock becoming a conductive material for low water saturation values.

Resistivity Index (RI) values increase with increasing pressure and decreasing water saturation (Figures 3-8) as more water is pushed out making the samples to resist electrical current passing through. From the analysis results obtained, saturation exponent value varies as a function of the water saturation and capillary pressure. Amount of water dropout from the core plugs is dependent on the capillary pressure as it increases from 1.0 - 60.0 psi. The saturation exponent which is calculated using log RI/log Sw has different values because with an increase in capillary pressure, more water drops from the sample rock thereby increasing the RI of the samples; with decrease in water saturation, the resistivity of the Formation increases. These resistivity values increase for data corrected for clay content. This means that with burial (increase in depth), compaction and therefore induration in the study field, much of the water will be squeezed out of the sediment thereby making the Formation highly resistant to electrical current that would be flowing through it. When irreducible water saturation level was reached for the core samples, volume of water left was held on the grain of the rock due to capillary pressure. Hence, the relative permeability of the rock to water at this point in the medium equal zero [18].



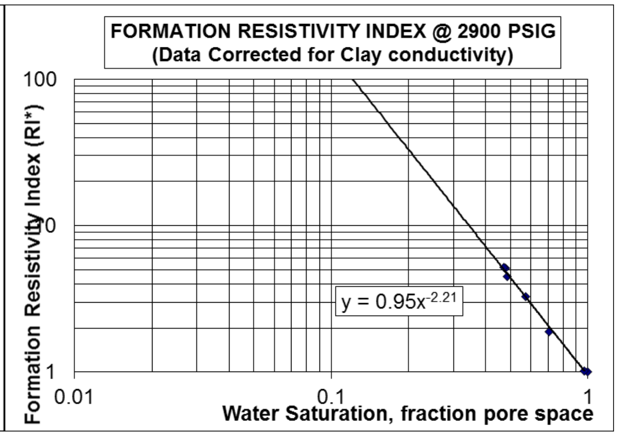
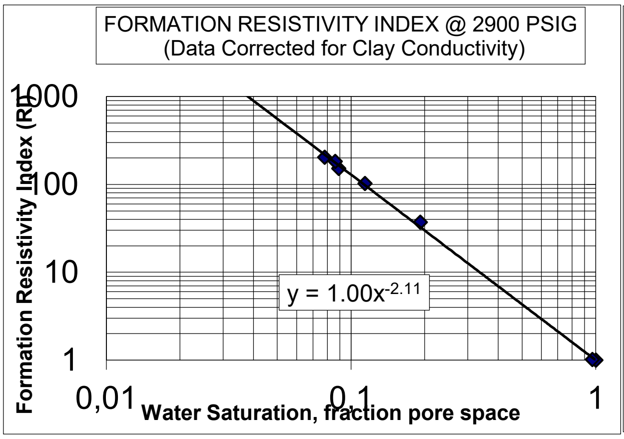


Figure 4. Resistivity Index vs water saturation for sample A Figure 5. Resistivity Index vs water saturation for sample B



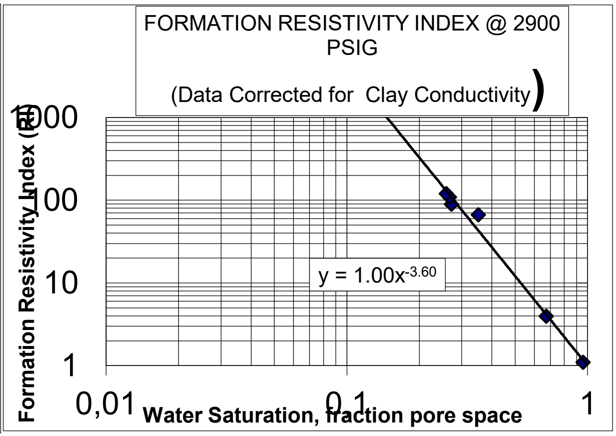
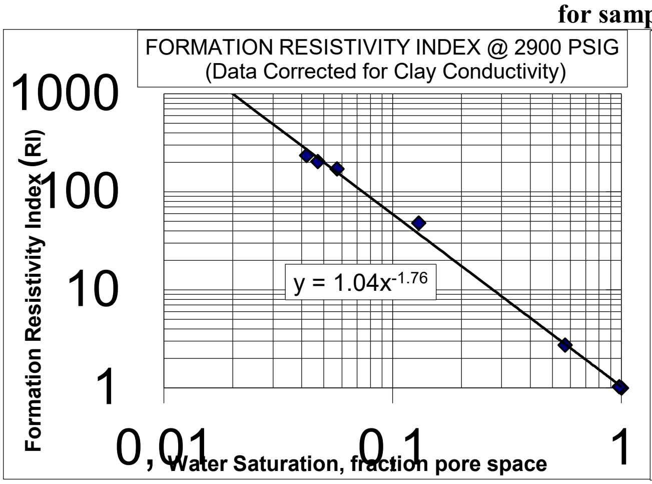


Figure 6. Resistivity Index vs water saturation for sample C Figure 7. Resistivity Index vs water saturation for sample D



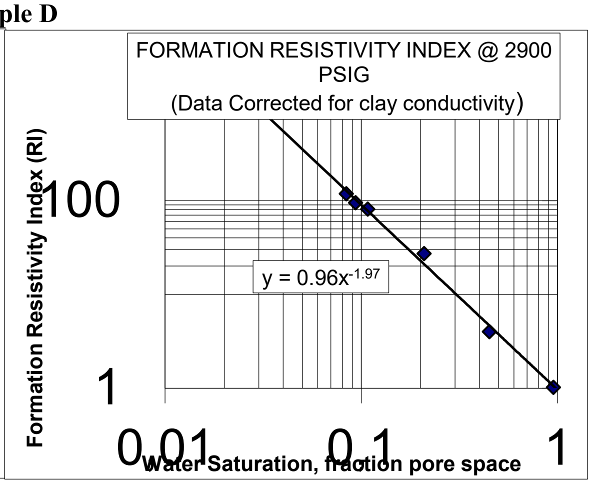


Figure 8. Resistivity Index vs water saturation for sample E Figure 9. Resistivity Index vs water saturation for sample F

4 CONCLUSION

From this study, it is observed that resistivity index gradually decreases as water saturation increases from <1 to1 which is at 100% saturation in the core plugs used. Resistivity index provides an expression of resistivity for a Formation flow system and it directly relates to the degree of water saturation in a particular medium. Results suggest that the interpretation of fluid saturation from electrical resistivity measurement takes into account the flow condition and pressure acting at a time at the subsurface. Saturation-resistivity relationship in a particular Formation will depend on the wettability, content of clay minerals present, saturation level, the salinity of the fluid in place in the Formation. An increase in overburden pressure from 500 psig to 2900 psig in this Formation reduces water saturation and permeability but increases cementation exponent, resistivity index and the formation resistivity factor across all samples as observed in Tables 2-7. In Table 2 for instance, with an increase in confining pressure from 500-2900 psig, porosity decreased from 0.337 to 0.314, Formation resistivity factor increased from 5.01 to 6.02 and cementation exponent increased from 1.49 to 1.56. These changes in the measured parameters for the Formation under study will have a significant effect on the water saturation and the electrical response when current is passed through the Formation

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