ELECTRICAL AND PETROPHYSICAL PROPERTIES OF SHU'AIBA RESERVOIR, SAUDI ARABIA

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ABSTRACT
Electrical parameters are of great importance to interpreting electrical logs and delineating hydrocarbon saturations in reservoir rocks. The applicability of these parameters in reservoir calculations is, in many cases, reservoir specific. Therefore, it is imperative that determination of these parameters in the laboratory should be conducted on selective core samples that represent the distinctive rock types and geologic facies.

An experimental program has been conducted to determine the electrical and petrophysical parameters of Shu'aiba carbonate reservoir, which is located in southeastern Saudi Arabia. Shu'aiba reservoir is a heterogeneous carbonate formation with various facies due to digenetic alteration of the original rock fabric. The measured electrical and petrophysical properties include formation resistivity factor FRF, cementation exponent **m**, saturation exponent **n**, porosity ϕ, permeability **K**, capillary pressure $\mathbf{P_c}$, and irreducible water saturation $\mathbf{S_{wir}}$.

The results revealed that changes in electrical parameters are accompanied by changes in rock type and geologic facies. When combined with conventional hydraulic radii models and NMR surface area models additional information for characterization and correlation is obtained.

INTRODUCTION
Lower Cretaceous formation (Shu'aiba) is one of the most productive carbonate reservoirs in the Middle East. It is a heterogeneous carbonate formation with five facies (Rudist barrier, fore barrier, back barrier, lagoon, and open platform) due to diagenetic alteration of the original rock fabric. Variation of geologic facies and rock structure lead to formation of different rock types. This will result in change of electrical properties for each rock type. There are several factors, which can influence the electrical parameters of carbonate rock reservoir. Inherent heterogeneities of Shu'aiba (carbonate) reservoir cause variation in texture, facies, and petrohysical properties [1]. Variations of rock texture and facies lead to formation of different rock types that produce changing values for m, n, and FRF.

Accurate determination of water saturation from resistivity logs depends on the correct assignment of the electrical parameters a, m, and n in the Archie equations [2]. These are determined from values of porosity, water saturation, water resistivity, and sample resistivity measured on representative core samples. Empirically the parameters are related by the equations:

$$FRF = R_o/R_w = a/\phi^m \quad (1)$$
$$FRI = R_t/R_o = 1/(S_w)^n \quad (2)$$
$$Sw = [a/\phi^m . R_w/R_t]^{1/n} \quad (3)$$

Where:

S_w = Water Saturation, FRF = Formation Factor, FRI = Resistivity Index, ϕ = Porosity, a = structural parameter = 1, R_o = Sample Resistivity at 100% Brine Saturation, R_w = Brine Resistivity, R_t = Measured (true) Sample Resistivity, n = Saturation Exponent, m = Cementation Exponent

In this study, an experimental program has been conducted to determine the electrical properties and explain the effect of rock type, facies and petrophysical parameters on change of electrical parameters for Shu'aiba reservoir.

EXPERIMENTAL APPROACH

Brine Preparation

Synthetic saturating brine was prepared on a weight basis using reagent grade salts and distilled water. The composition of the brine matched the average water analyses of the Shu'aiba reservoir brine. Brine resistivities were calculated from the equivalent sodium chloride concentration using published correlations [3,4]. **Table 1** presents the composition of the synthetic formation brine used to saturate the core plugs.

Sample Selection

Samples were selected to represent the basic reservoir quality units and flow zone units in the reservoir. These units are based on variations in specific surface area established from a Carmen-Kozeny model relating porosity and permeability. Using the description of Nelson [5], the terms defined by Amaefule [6], correlations developed by Archie [1] and Paterson [7] the surface area can be calculated with the equations:

$$RQI\ (microns) = 0.0314x\ [K(md)/\phi]^{1/2} \quad (4)$$
$$K = C\ x\ \phi^3/[(1-\phi)^2 . S^2_{Grain\ Volume}] \quad (5)$$
$$C = f/\phi^{(1-m)} \quad (6)$$
$$S_{Grain\ Volume} = C^{1/2}/RQI\ x\ \phi/(1-\phi) \quad (7)$$
$$Surface\ Area = S_{Grain\ Volume} / \rho_{Grain} \quad (8)$$

Where:

K = Permeability to air (md), C = Carmen – Kozeny Constant, ϕ = Porosity, f = Shape factor, m = Cementation Exponent, $S_{grain\ volume}$ = Specific Surface/Unit Grain Volume.

Measured and calculated values for the tested samples are listed in **Table 2**.

Resistivity Measurements

Brine saturated core plugs were placed in electrically isolated core holders with a water wet (75 psi) porous plate end-plug located on the effluent end. Electrical contact was maintained via silver membranes placed between the current electrodes and the core sample. Resistivity measurements were made with a Fluke 254C RLC Impedance Analyzer linked to a HEWLETT PACKARD 3852A Data Acquisition Unit. The in-house-developed microcomputer controlled system provided resistivity measurements, pressure, and temperature monitoring on eight core samples along with monitoring of an internal resistance standard. Variations of more than 1% in the internal resistance standard were used as criteria to reject resistivity measurements on samples within individual cells. These criteria established the confidence interval for the formation resistivity factor measurements on all samples but eliminated two samples (7 and 8) from formation resistivity index determinations.

Resistance and capacitance of the individual samples were measured continuously at 2,950-psi net overburden pressure and 25 ^{o}C. Resistivities were corrected to a base temperature of 23^{0} C using the Arps equations:

$$R_t = [r_t \,.\, (A/L) \,.\, TF]/100 \qquad (9)$$

$$TF = (1.8T + 39)/80.4 \qquad (10)$$

Where:
R_t = Rock Resistivity (ohm-meters), r_t = Measured Rock Resistance (ohms), A = Area of Rock Face (cm^2), L = Length Between Voltage Measurement Electrodes (cm) TF = Temperature Correction Factor, T = Measured Temperature (^{o}C)

Formation Resistivity Factor and Cementation Exponent

Formation resistivity factor ratios (FRF) were determined from the resistivity of 100% brine saturated samples (Ro) and the resistivity of the saturating brine (Rw). Individual cementation exponents were determined directly from Equation (1) using the measured formation resistivity factor, overburden porosities, and an assumed “a” value of 1. Average cementation exponents were determined from the straight-line logarithmic fits of formation resistivity factor (FRF) with overburden porosity (**Figure 1**).

Formation Resistivity Index and Saturation Exponent

Samples were desaturated using air at approximately six different capillary pressures and resistivity measurements made at each saturation value. Desaturation capillary pressures were increased when no further desaturation was observed and resistivity values had stabilized.

Resistivity values were plotted as a function of brine saturation (Sw) and saturation exponents were determined from bilogrithmic plots of formation resistivity index (FRI) and brine saturation (Sw). Saturation exponents for the tested plugs are listed in **Table 2** except plugs # 7 and 8. Tested samples showed an average saturation exponent of 2.05 (**Figure 2**).

RESULTS AND DISCUSSION

Formation Resistivity Factor

As shown in **Figure 1**, most lagoon samples (lagoonal and lagoonal miliolid facies) are within the range of the aphanatic limestone samples tested earlier [8]. However, the distribution of the tested samples is skewed to higher formation factor values. In addition to the distribution, cluster analyses and logarithmic plots of formation resistivity factor (FRF) versus porosity indicate that there is a distinction between samples in the interval above D-61 ft and those below D-85 ft. The two correlations are shown in **Figure 1**, where the upper samples (excluding sample #5) show a cementation exponent of 2.06 and the lower samples show a cementation exponent of 1.82. These formation resistivity factors indicate that the samples are moderately consolidated with slightly more consolidation in the upper samples.

Formation Resistivity Index and Saturation Exponent

Tested samples showed an average saturation exponent of 2.05 (**Figure 2**). Two aspects of the resistivity measurements need to be considered in the interpretation of the saturation exponent plot. These are matrix mineralogy and conductivity and sample wettability.

Since sample resistivities were measured with one brine composition and correspondingly one brine resistivity, the effect of matrix conductivity could not be established. However, when conductive clays and minerals are absent, this is not a significant concern. The absence of these conductive materials is supported by the CT scans which show only slight variations in CT number. In carbonate systems, conductive minerals and clays would result in substantially larger CT number variations.

The tested samples had been cleaned and extracted using a toluene distillation/extraction process. This procedure tends to render the samples strongly water-wet. Hence, from a wettability consideration the saturation exponents determined from these water-wet samples should be considered as a lower limit.

Reservoir Quality Index (RQI) and Specific Surface

The RQI values and specific surface areas of the samples are typical for the permeability range of the samples and typical of the productive interval in the selected well (A). Although there are slight slope changes in the cumulative RQI plot (**Figure 3**) indicating some reservoir heterogeneity, all samples lie along one of the dominant RQI versus depth trends for this well.

Specific surface values are a useful tool for evaluating pore size data. In samples where the RQI model is accurate, the specific surface will correlate with median pore radii from mercury injection or NMR geometric mean T2. A secondary check of the specific surface values is through the calculation of surface areas using Equation (8). Results are listed in **Table 2**. Specific surface values for the samples are similar. Calculated surface areas are slightly above the (0.41 m^2/g) range seen in Arab-D carbonates, but are in close agreement with published values for carbonates.

Capillary Pressure

Equilibrium values of air/brine capillary pressure along with measured brine saturations were used to construct capillary pressure curves shown in **Figure 4**. Three samples (#2,

#5, and # 6) showed asymptotic capillary pressure indicating that final irreducible water saturations (S_{wir}) were achieved.

SUMMARY

1. Cluster analyses and logarithmic plots of formation resistivity factor (FRF) versus porosity indicate distinct differences between samples in the interval above D-61 ft. and those below D-85 ft. The upper samples have an average cementation exponent of 2.09, while the lower samples show an average cementation exponent of 1.82.
2. Samples showed an average saturation exponent of 2.05. However, the tested samples had been cleaned and extracted using toluene. This cleaning process may render the samples to be strongly water-wet. Therefore, based on wettability, the saturation exponents determined from these water-wet samples should be considered as a lower limit.
3. Reservoir quality index (RQI) values and specific surface areas of the samples are typical for the permeability range and typical for the productive interval in Well-A.

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Table 1. Composition of the Synthetic Brine Used in the Tests.

Variable	Value	Variable	Value
NaCl, g/L	131.61	Total dissolved solids (TDS)	185.90
$CaCl_2.2H_2O$, g/L	59.98	Density, g/cc	1.1225
$MgCl_2.6H_2O$, g/L	16.60	Salinity, ppm	164,964
Na_2SO_4, g/L	00.49	NaCl Equivalent salinity, ppm	155,134
Total salt	208.68		

Table 2. Reservoir Characterization Parameters.

Plug No.	Depth (ft.)	Φ (%)	K (md)	RQI (microns)	Specific Surface (microns $^{-1}$)	Surface Area (m^2/g)	m	n
1	D44.6	25.8	4.3	0.131	1.77	0.65	2.16	1.9
2	D45.1	24.8	1.3	0.070	1.61	0.59	2.07	2.9
3	D46.1	26.9	7.8	0.173	1.43	0.53	2.17	2.4
4	D58.5	25.6	5.9	0.151	1.22	0.45	2.08	1.5
5	D60.5	23.0	3.3	0.119	1.50	0.56	1.99	1.9
6	D85.6	21.6	5.1	0.153	1.15	0.43	1.84	1.8
7	D104	22.9	4.5	0.139	1.44	0.53	1.82	-
8	D105	23.0	3.6	0.125	2.00	0.74	1.81	-

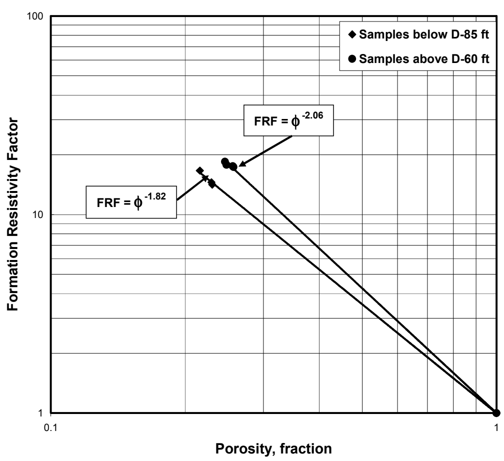

Figure 1. Interval Avg. Formation Resistivity Factor.

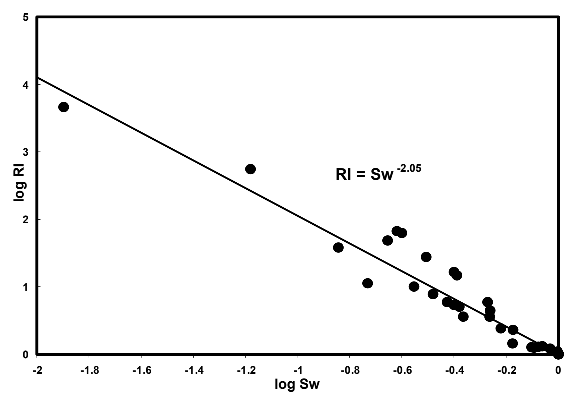

Figure 2. Composite Resistivity Index.

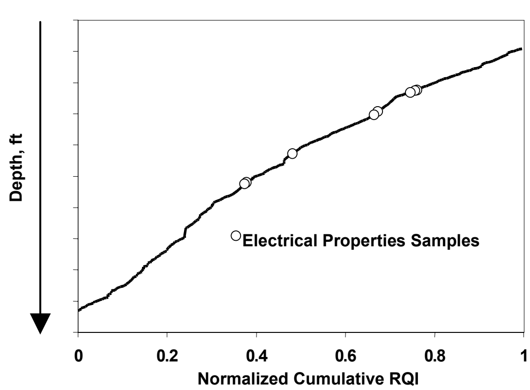

Figure 3. Cumulative RQI Plot.

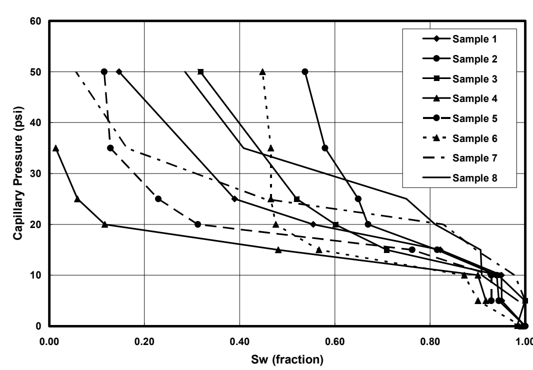

Figure 4. Capillary Pressure Curves.