Effect of Pore Geometry on Reservoir Rock Properties

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Abstract: This study has been undertaken in three oil fields (A-Libya, B-Libya, and C-Libya) in sirte basin located in Libya. Nubian sandstone Formation is the main reservoir in the studied oil fields. Laboratory measurements methods were applied on the core samples that were selected from three different fields of Nubian Sandstone. Some of these measurements were conducted in Libyan Petroleum Institute (LPI Tripoli-Libya) laboratories in order to determine the resistivity parameters of the central graben reservoir cores and to investigate the effect of rock hetrogeneity and wettability on the resistivity parameters of Nubian sandstone reservoir rocks. The pore size distribution was estimated from generated capillary pressure curves. The samples belonged to Nubian sandstone, Sirt basin were selected to perform formation resistivity factor measurements.

The Pore size distribution and type of pores were calculated from mercury injection capillary pressure data. The results indicated that changes had been observed in formation resistivity factor and cementation exponent when overburden pressure was applied (slightly increases in cementation exponent with increasing O.B.P). Wettability played an important role in determining the fluid movement, distribution and electrical conduction during desaturation processes. Resistivity index effect has been observed after wettability measurement showing oil-wet tendency.

From the results obtained, a good relation between resistivity and type of pores (macro and micro pore system) was observed. When oil begins to penetrate micro-pore systems during the measurements, a significant change in slope of the resistivity index relationship occurs.

Keywords: Nubian Sandstone, resistivity, Heterogeneity, Micro-porosity, Electrical properties.

INTRODUCTION

The amount of hydrocarbon reserves is one of the most important parameters in the decision making process in developing a reservoir.

The interpretation of logging data is based on Archie's law. Electrical logging is the most widely used method of identifying hydrocarbon intervals in wellbore. Standard method of relating oil saturation in clay free reservoirs to electrical resistivity is based on Archie saturation equation (Archie 1942):

$$RI = \frac{Rt}{Ro} = Sw^{-n} \quad (1)$$

Where the resistivity index, *RI*, is equal to the ratio of the resistivity of the sample (*Rt*) at brine saturation (*Sw*) over the resistivity of the sample at one hundred percent brine saturation (R_o). The resistivity index is related to the saturation of the sample and the saturation exponent (***n***). The saturation exponent must be determined by experimental core analysis. The standard technique for determining the saturation exponent involves measurements in cleaned cores, usually with air as the non-wetting phase and brine phases. Thisair/brine system is only representative of the drainage conditions in strongly water wet situations. When oil displaced by water, for instance during water flooding, different distributions of fluid may prevail at the pore scale due to hysteresis effects controlled by pore geometries, initial saturation and wettability distribution at the pore scale. When the rock is compacted as a result of overburden pressure, the matrix is under stress and porosity decreases as a result of compaction, cementation factor will change. ***Wyble*** (***1958***) found a systematic decrease in the rock conductivity and an increase in formation factor as the overburden pressure increased over the range of 0 to 3500 psi using core samples. In the study carried out by Wyble, an increase in formation factor of up to **6.6** percent of original value measured at zero overburden pressure. Cementation exponent of one of the samples studied was increased from 1.87 to 2.04 as a result

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of increasing the pressure up to 5000 psi. Porosity of sedimentary rocks can be classified according to their pore size distribution as macro- and micro-porosity. Vuggy and fracture porosities are characteristics of macro-porosity because large pore geometries are associated with vugs and fractures.

Pore system associated with macro-porosity has an average pore diameter greater than 1/16 mm (Pittman, 1971) where most of the hydrocarbon volume accumulates. Permeability is strongly dependent on the amount of macro-porosity. Micro-porosity is associated with pores whose diameter is less than 1/16 mm (Pittman, 1971). Micro-porous system is characterised by a high capillary pressure, which tends to retain high amount of irreducible water resulting in high formation electrical conductivity (low resistivity).

Wettability plays a major role in controlling the distribution of fluids within the pore space inside a rock. Keller (1953***)***, Presented evidence that saturation exponent could be substantially different from 2.0. He found that Archie's saturation exponent (*n*) varies from 1.5 to 11.7 for the same rock, depending on how cores were treated. For the same water saturation, resistivity of an oil reservoir can vary thousand times for different wetting conditions. The wettability of sandstone cores was altered from water wet to oil wet conditions by using various chemical treatments. Keller concluded that the wettability played a great role in the fluid distribution within the rock space. By changing the relative position of the conducting fluid with respect to the rock surface, the electric behaviour of fluid filled sandstone would also change. A measurement of capillary pressure curves as a means of determining pore size distribution was first suggested by Washburn (1921). This principle was fairly accepted and the majority of the pore size distribution measurements have been determined by the mercury injection procedure.

OBJECTIVE OF THE STUDY

- Investigate the effect of rock heterogeneity and wettability on resistivity parameters of sandstone reservoir rocks, Nubian sandstone.
- Quantify experimentally pore and porosity types.
- Investigate the effect electric properties on micro-porosity rocks

METGHODOLOGY

The clean, dry samples were subjected to various analyses to determine porosity, permeability and grain density values where possible. The equations used to calculate porosity and permeability as follows:

$$\phi = \frac{V_P}{V_b} = \frac{V_P}{V_P + V_g} \qquad (2)$$

$$Kg = \frac{2000 \times Pa \times Q \times \mu_g \times L}{(P1^2 - P2^2) \times A} \qquad (3)$$

The samples belong to Nubian sandstone from three oil fields (Table 1); Sirt basins were selected to perform formation resistivity factor measurements.

Formation resistivity factor is calculated as the ratio of the sample resistivity to the resistivity of the water saturating it. The formation resistivity factor of a group of samples is plotted versus their porosities on log-log graph paper. The slope of the best fit line is the value of the cementation factor, "*m*" and the intercept is the value of, "*a*"

$$FF = \frac{a}{\phi^m} \qquad (4)$$

The previous samples were used for the formation resistivity factor measurements at room conditions and scheduled for formation factor testing at overburden pressure (1000- 5000 psi), and formation resistivity index test either.

The wettability measurement (Amott method), was conducted on the same samples, after that the samples were selected to perform capillary pressure measurement. Mercury injection offers an alternative system for the study of capillary pressure.

Table 1. Porosity and Permeability valuesof the studied wells.

Samples#	Well Name	Ø (%)	K(mD)
03	A1-Libya	10.39	337.5
10	A1-Libya	9.01	34.11
15	A3-Libya	12.17	12.55
18	B1-Libya	14.59	1146
24	A3-Libya	8.01	9.910
29	C2-Libya	17.38	69.86
41	C1-Libya	15.34	660.4
42	A3-Libya	11.71	4.901
47	C2-Libya	17.91	279.7
53	A1-Libya	11.16	297.7
83	A2-Libya	9.56	27.73
123	A2-Libya	12.76	118.1

Mercury injection method entails injecting mercury into a clean dry sample and monitoring the injection pressure and the amount of mercury injected into the rock sample.

Pore size distribution can be calculated from mercury injection capillary pressure data; however, a broad range of pore size and type is covered by mercury injection capillary pressure. The pore throat radius is calculated as:

$$r_p = \frac{2\sigma\cos\theta}{P_c} \quad (5)$$

EXPERIMENTAL MEASURMENTS

Laboratory measurements methods were applied on the core samples that were selected from three different fields of Nubian Sandstone (Fig. 1) Some of these measurements were conducted in Libyan Petroleum Institute (LPI Tripoli-Libya) laboratories in order to determine the resistivity parameters of the central graben reservoir cores and to investigate the effect of rock hetrogeneity and wettability on the resistivity parameters of Nubian sandstone reservoir rocks.

Capillary pressure curves have been generated and the pore size distribution estimated.

RESULTS AND DISCUSSION

Twelve Sandstone core samples were selected from three oil fields (six wells) had porosities between 8.01-17.91% and permeability range from 4.90mD to 1146 mD are presented in Table 1 while the other properties such as formation resistivity factor, porosity and cementation exponent for the same samples were measured and tabulated in Table 2.

In the measured cores a well-defined relationship exists between formation resistivity factor and porosity. The formation resistivity factor was best fit to Archie's equation so that the coefficient (*a*) and cementation factor were determined. The data was fit to Archie equation by assuming *a*=1, and the value of m was calculated for each sample. The average cementation factor for all the core samples of Nubian sandstone was calculated from slope of the best fit straight line through the points. The average value of cementation factor was 1.69 and the correlation coefficient, R^2, was 1.0. In this study, both formation resistivity factor (***FF***) and cementation factor (***m***) were found increase with confining pressure for the Nubian sandstone samples.

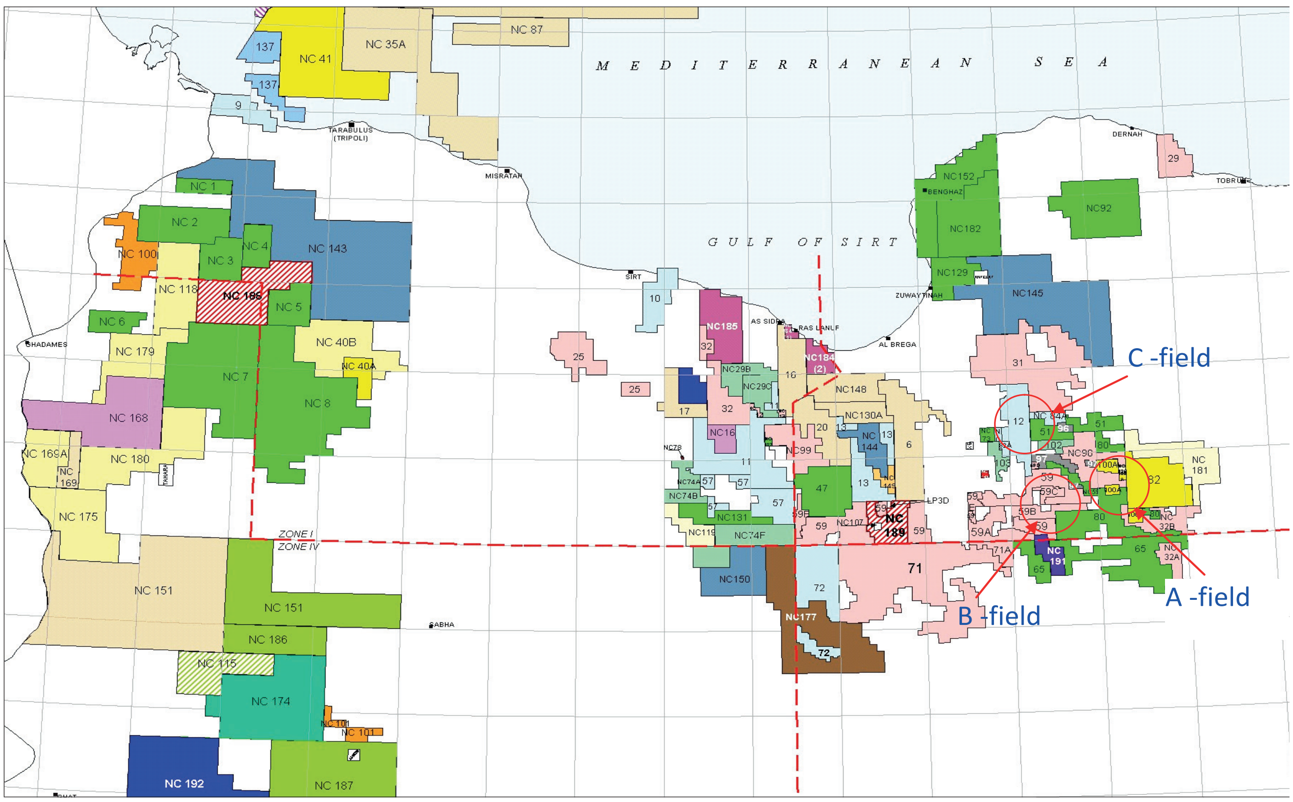

Fig. 1. Illustrate location oil fields proposed in this study

Table 2. Porosity, formation resistivity factor and cementation exponent of Nubian sandstone core samples at ambient conditions

Sample #	Porosity (%)	Formation res. Factor (F.F)	Cementation exponent "m"
03	10.39	41.6	1.65
10	9.01	52.8	1.65
15	12.17	44.6	1.80
18	14.59	23.9	1.65
24	8.01	60.4	1.62
29	17.38	20.3	1.72
41	15.34	23.3	1.68
42	11.71	41.8	1.74
47	17.91	20.0	1.74
53	11.16	36.8	1.64
83	9.56	59.0	1.74

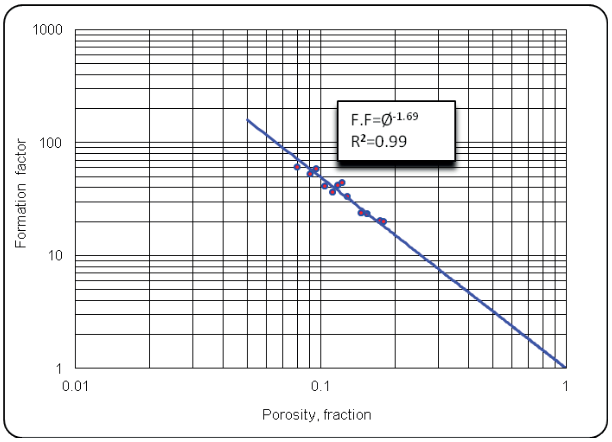

Fig. 2. Porosity versus formation resistivity factor at ambient conditions

Table 3 and Fig. 3 displaying the experimental results of the effect of overburden pressure on cementation factor. These results indicate that the cementation factor (**m**) changes at various confining pressure from 1000 to 5000 psi and the rock is compacted as a result of overburden pressure, the matrix is under stress and porosity decreases as a result of compaction , therefore, cementation factor will change.

Wettability was measured for the same samples which taken from Nubian sandstone; data in Table 4 show the results of saturation exponent (***n***) before and after wettability measurement.

(Fig. 4) shows the relation between resistivity index and water saturation before and after

Table 3. Cementation factor values at overburden pressure for the samples

Overburden pressure psi	Cementation exponent (m)
1000	1.71
2000	1.72
3000	1.74
4000	1.75
5000	1.76

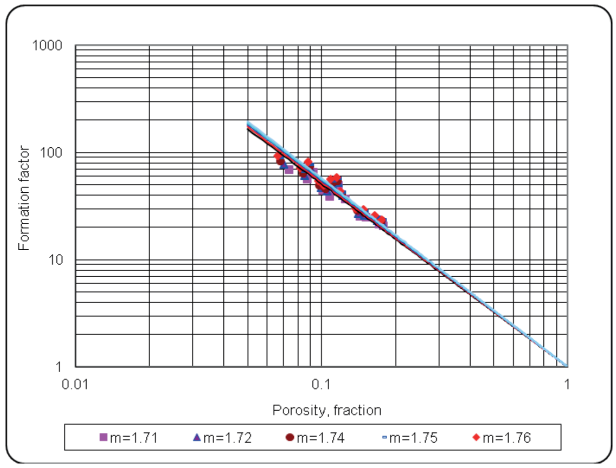

Fig. 3. Porosity versus formation resistivity factor at different overburden pressures

Table 4. Archie's saturation exponent values before and after wettability measurement

Sample #	Well Name	Saturation Exponent(n) Before wettability	Saturation Exponent(n) After wettability
03	A1-Libya	1.39	2.39
10	A1-Libya	1.75	2.60
15	A3-Libya	2.06	2.79
18	B1-Libya	1.76	2.65
24	A3-Libya	1.93	2.18
29	C2-Libya	1.79	2.59
41	C1-Libya	1.87	2.50
42	A3-Libya	2.18	2.86
47	C2-Libya	1.91	2.65
53	A1-Libya	1.78	2.43
83	A2-Libya	1.97	2.49
123	A2-Libya	1.73	2.22

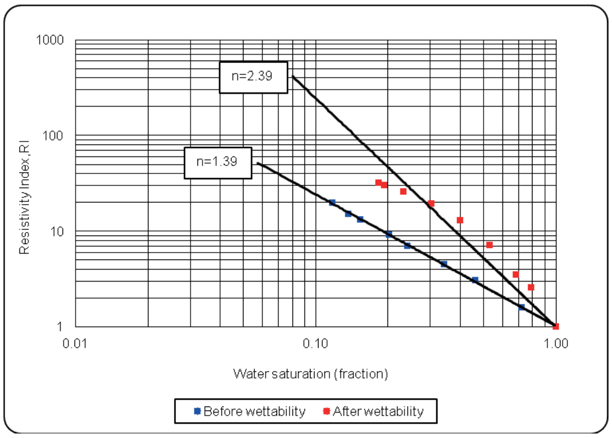

Fig. 4. Resistivity index versus water saturation before and after wettability test of sample # 3

wettability for sample #**3.** The Saturation exponent before wettability measurement was **1.39,** When wettability measurement conducted on the sample, the sample imbibed oil (tendency to oil wet), so the saturation exponent increased to **2.39**. However, slightly higher saturation exponent was obtained. The results indicate that the effect of wettability on saturation exponent (***n***) is more significant in second stage (after restoration).The increase in resistivity and saturation exponent in oil wet cores compared to water wet cores explained by (Anderson, 1986). In oil wet core, the wetting phase (oil) tends to occupy the smaller pores and to contact the majority of rock surface, while the non-wetting phase (brine) is normally located at the centre of the large pores. A fraction of the non-wetting phase (especially at low brine saturation) become disconnected and surrounded by oil which acts as an insulator to the flow of electric current. The insulation of this portion of brine prevent it from contributing to the flow of electric current and hence lead to a higher values of saturation exponent.

Fig. 5 shows the resistivity index versus water saturation and mercury saturation capillary pressure curves of sandstone sample-**3**. Excellent relation between resistivity and pore type system was observed. Note that the saturation where mercury penetration into micro-porosity occurs, a significant change in slope of the relationship between resistivity index and brine saturation of rocks containing micro-porosity as well. The change in slope may be due to micro-pores/irregular surfaces through these samples. The reason is that, as oil saturation increases, first the resistivity is dominated by the large pore network. Water saturation is still high because micro-pores hold up large water volume, high apparent saturation exponent results. Then as capillary pressure increase sufficiently to penetrate the micro- pores, water drain from micro-pores with very little influence on resistivity, then saturation exponent (***n***) decreases.

CONCLUSIONS

- The results showed that changes had been observed in formation resistivity factor and cementation exponent when overburden pressure was applied (slightly increases in cementation exponent with increasing O.B.P).
- Wettability played an important role in determining the fluid movement, distribution and electrical conduction during desaturation processes. i.e. Samples with an oil-wet tendency, for example, sample#3 have higher irreducible brine saturation and higher Archie saturation exponent values than samples with uniform water-wet surface.
- Resistivity index effect has been observed after wettability measurement showing oil-wet tendency.

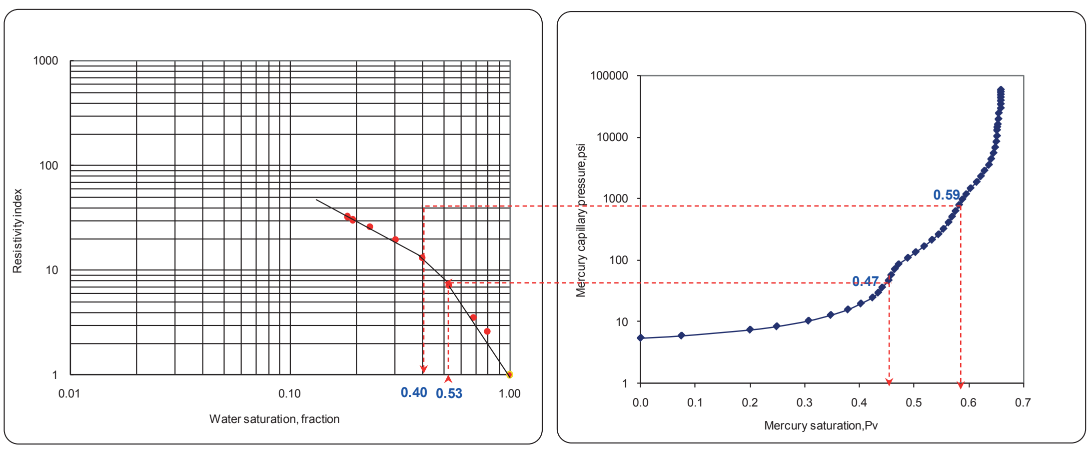

Fig. 5. Relation between resistivity and type of pore system of sample # 3

- From the results obtained, a good relation between resistivity and type of pores (macro and micro pore system) was observed. When oil begins to penetrate micro-pore systems in measurements of resistivity index versus brine saturation, a significant change in slope of the resistivity index relationship occurs.

Nomenclature

a = A constant in Archie's equation
A = Cross-Sectional area, cm^2
FF = Formation resistivity factor.
K = Permeability, mD
L = Length, cm
m = Cementation factor, dimensionless
n = Archie's saturation exponent.
P1 = Upstream Pressure, atm
P2 = Downstream Pressure, atm
Pa = Atmospheric pressure, atm
Pc = Capillary pressure, psia
ΔP = Pressure differential, atm
Q = Volumetric flow rate, cc/sec
r_p = Pore throat radius, μm
R_w = Water resistivity, Ω.m
R_t = True resistivity, Ω.m
R_o = Rock resistivity, Ω.m
RI = Resistivity index, dimensionless
S_w = Water saturation, fraction
V_p = Pore volume, cc
V_b = Bulk volume, cc
V_g = Grain volume, cc
Ø = Fractional porosity
q = Contact angle, degree
μ = Fluid viscosity, cp
s = Interfacial tension, dyne/cm

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