

A NEW APPROACH TO CORRECT FOR ROCK CONDUCTIVITY IN CONJUNCTION WITH CORE PLUG RESISTIVITY MEASUREMENT AND INTERPRETATION OF RESISTIVITY LOGS

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Abstract

An empirical equation has been developed to correct resistivity data from core plugs and logs. A combination of rock conductivity dependent on water salinity, conductivity as a result of the interaction between cations in brine and shale, and conductivity of the rock itself may occur in reservoir sediments.

The commonly used Waxman and Smits¹⁾ equation incorporates a rock conductivity which is result of the cation exchange between the brine and the rock, i. e. the clay portion of the rock matrix. A new model has been established by introducing the possibility of the rock itself to conduct electrical current, combined with the Waxman and Smits¹⁾ model. For reservoir rocks with high matrix conductivity, it is shown that the conventional Waxman and Smits¹⁾ correction indicates abnormally high water saturation in oil zones.

The introduction of this new concept has proved its usefulness in a case study. The study presents resistivity data of core plugs from porous plate drainage including multiple salinity measurements (C_oC_w). The saturation n-exponents have been corrected to values applicable for log interpretation.

Secondary log evaluation, using the new method for resistivity correction, show a increase in net-pay for the reservoir.

Introduction

In 1968, Waxman and Smits¹⁾ proposed a saturation-resistivity relationship for shaly formations that related the resistivity contribution of the shale to the overall resistivity of the formation. Only the porous part needs to be considered when discussing electrical properties, and this part may be treated according to the Archie's³⁾ water saturation equation. Waxman and Smits¹⁾ concluded that the model could be used for most rocks, except for rocks containing conductive minerals such as pyrite.

Drainage capillary pressure measurements, using porous plate technique, have been carried out on 6 core samples from a North Sea field. During the drainage process on four of the core samples, low or minor changes in resistivity behaviour as a function of desaturation were observed. Low resistivity was observed in the interpretation of well logs for the

reservoir interval where the four core plugs had been selected. All resistivity measurements indicated high water content in this zone.

Preliminary log evaluation

The preliminary analysis done offshore based on the logs, indicated no net pay present in the lower section of the reservoir. This was based on the log response from the resistivity logs, gamma ray, and density/neutron. However, the well was perforated and a production test was performed. The well produced hydrocarbons also from the lower section, with no trace of water.

The whole core in this interval contained sand with fairly good porosity and permeability. Routine measured grain densities showed abnormally high values of 2.80-2.90 g/cm³. A new log interpretation was performed to match the core porosity values in this zone using an average grain density of 2.82 g/cm³. A good match was obtained but the calculated water saturation indicated water wet properties in this interval. The difference between the clay bound water measured by the Magnetic Resonance Image Log (MRIL) and the calculated water saturation indicated that the zone contained movable water. This conclusion could not be supported by pressure measurements, the interpreted fluid contact in the area, or the well test data.

Mineralogy

Core plugs covering the whole reservoir section were chosen for x-ray diffraction analysis. The results show an abrupt change in mineralogical composition in the lower part of the reservoir.

In the upper section of the reservoir, the quartz abundance is typically in the range 70 - 90 wt % with relatively small amounts of clays, carbonates and pyrite. Inside the lower section, the maturity of the samples is low with quartz in the range 30 - 60 wt % and the total clay content including mica increases to 3-4 times the amount above. The most dramatic change is, however, the increase in the pyrite abundance, from less than 1 wt % to abundances between 3 wt % to 23 wt %. In addition, apatite and gypsum are common in the lower section.

Scanning electron microscopy and optical microscopy of thin sections show that the clays in both sections are detrital or pseudomorphs after micas and lithoclasts and some pore-filling kaolinite. The apatite is mainly bone fragments, so optical microscopy reveals a high abundance of organic matter as structured wood or plant fragments, and amorphous, semi-translucent masses.

The pyrite is authigenic in origin and occurs as dispersed microcrystals and framboidal aggregates throughout the examined samples. On many grains it is present as a continuous thin coating of microcrystals and it rarely occurs as poikilotopic cements or nodules. The nature and abundance of this pyrite probably influence both the density log and the resistivity measurements.

The gypsum is interpreted as a product of the oxidation of pyrite in the laboratory.

Reservoir Unit	Mixed layer illite-smectite	Illite/Mica	Kaolinite	Quartz	Alkali-feldspars	Plagioclase
Upper section	0.0	0.7	1.8	76.6	10.4	6.7
Lower section	0.1	1.9	4.7	51.8	15.2	3.9
Reservoir Unit	Calcite	Dolomite -Ankerite	Siderite	Pyrite	Apatite	Gypsum
Upper section	1.4	0.9	0.6	0.8	0.0	0.0
Lower section	2.6	1.0	0.9	13.2	3.7	0.9

Table 1: Whole-rock mineralogy based on X-ray diffraction analysis. (Semi-quantitative weight percentages)

Petrophysical properties for the core samples

Petrophysical properties for the 6 core plugs are presented in Table 2 and in Figure 1 and Figure 2.

Reservoir Unit	K_L	Φ	GD	n	S_{wi}	CEC	n^*	BQ_v
	20 bar	200 bar		200 bar	200 bar		200 bar	200 bar
	20°C (mD)	20°C (frac.)	20°C (g/cc)	81°C	81°C (frac.)	(meq/100g)	81°C	30 °C (Ωm) ⁻¹
Upper section	1288	0.294	2.64	2.12	0.114	0.67	2.22	0.160
	1191	0.301	2.64	1.82	0.105	1.00	1.95	0.235
Lower section	25.1	0.245	2.72	1.36	0.476	2.20	1.72	2.091
	24.5	0.217	2.81	0.49	0.478	1.40	1.26	13.155
	12.8	0.169	2.72	1.35	0.248	0.90	1.71	1.650
	0.663	0.106	2.73	1.41	0.432	0.85	1.73	1.661

Table 2: Petrophysical properties.

n : Uncorrected saturation exponents.

n^* : Corrected saturation exponents using traditional Waxman and Smits¹⁾ equation.

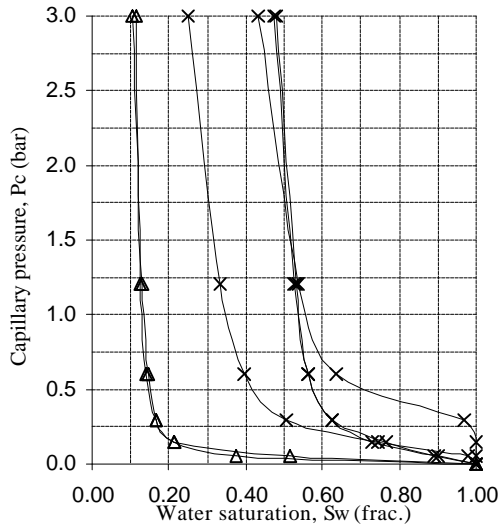


Figure 1: Capillary pressure versus water saturation.

- Δ: Core plugs with normal resistivities.
- X: Core plugs with abnormal resistivities.

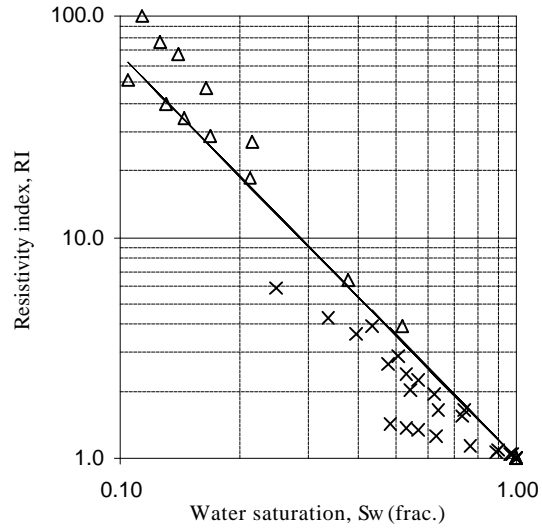


Figure 2: Uncorrected resistivity data for the core samples.

For the upper reservoir section, the data indicates a sandstone with minor shale content.

For the lower reservoir section, high grain density compared with extremely low saturation exponent, and the high value for BQ_V , indicates influence of other parameters with respect to changes in resistivity. Calculated saturation exponents from traditional Waxman and Smits¹⁾ equation, confirm that Waxman and Smits¹⁾ theory can not be applied for high values of BQ_V . The nature and abundance of pyrite from the mineralogical description of these four core plugs led to the assumption that the rock matrix itself was conductive.

A new model for resistivity correction

The correction for clay effect is traditionally determined using a Waxman and Smits¹⁾ correction for RI. By substituting the corrected RI into Archie's³⁾ equation we have:

$$RI^* = RI \cdot \left(\frac{C_w + \frac{B \cdot Q_v}{S_w}}{C_w + B \cdot Q_v} \right) = S_w^{-n^*} \quad \text{eq. 1}$$

The derived data for BQ_V can be expressed as a sum of the contributing parts.

$$(BQ_V)_T = (BQ_V)_C + (BQ_V)_m \quad \text{eq. 2}$$

Where $(BQ_v)_c$ represent the part of $(BQ_v)_T$ related to clay activity, and $(BQ_v)_m$ represent the part related to matrix activity.

To try to separate possible matrix conductivity from clay conductivity, it was decided to perform CEC measurements on all core plugs. The volume concentration of clay exchange cations or Q_v value was calculated using the following equation:

$$Q_v = \frac{CEC \cdot (1 - \Phi) \cdot GD}{100 \cdot \Phi} \quad \text{eq. 3}$$

Conductance associated with each cation, B, is dependent on temperature and water resistivity. If we assume constant temperature and constant formation water composition, B can be estimated as a constant for the plug interval in this study. B was calculated using data from the two first core plugs, by assuming no matrix activity with respect to conductivity. B was determined to be 3.79 $((\Omega m)^{-1} \cdot (\text{meq/cm}^3)^{-1})$ for both core plugs.

As a quality check, we calculated B using the graphical approach of I. Juhasz²⁾. By using the graphical approach, B was determined to be 3.60 $((Wm)^{-1} \cdot (\text{meq/cm}^3)^{-1})$, for the curve at 25° C. Now we can calculate the two separate terms as follows:

$$(BQ_v)_c = 3.79 \cdot \frac{CEC \cdot (1 - \Phi) \cdot GD}{100 \cdot \Phi} \quad \text{eq. 4}$$

$$(BQ_v)_m = (BQ_v)_T - (BQ_v)_c \quad \text{eq. 5}$$

It can be shown that the term in Waxman and Smits¹⁾ correction for RI converges when:

$$\lim_{BQ_v \rightarrow \infty} \left(\frac{C_w + \frac{(BQ_v)}{S_w}}{C_w + BQ_v} \right) = \frac{1}{S_w} \quad \text{eq. 6}$$

We assume that the Waxman and Smits¹⁾ correction for RI can be written as:

$$RI^* = RI \cdot (K_c \cdot K_m) \quad K_c = \frac{C_w + \frac{(BQ_v)_c}{S_w}}{C_w + (BQ_v)_c} \quad \text{eq. 7}$$

The matrix conductivity, C_m , can be determined theoretically from CoC_w data when there is no conductivity contribution from the formation water, i.e. when $C_0(C_w=0)$.

$$C_m = \frac{(BQ_v)_m}{FF^*} \quad \text{eq. 8}$$

We add C_m into the Waxman and Smits¹⁾ term and define K_m as:

$$K_m = \left(\frac{C_m + \frac{C_m \cdot (BQ_V)_m}{C_W \cdot S_W}}{C_m + \frac{C_m \cdot (BQ_V)_m}{C_W}} \right) \quad \text{eq. 9}$$

Now we can write the separated correction as:

$$RI^* = RI \cdot \left(\frac{C_W + \frac{(BQ_V)_C}{S_W}}{C_W + (BQ_V)_C} \right) \cdot \left(\frac{C_m + \frac{C_m \cdot (BQ_V)_m}{C_W \cdot S_W}}{C_m + \frac{C_m \cdot (BQ_V)_m}{C_W}} \right) \quad \text{eq. 10}$$

As a quality check on this equation, we have:

$$RI \cdot \left(\frac{C_W + \frac{(BQ_V)_T}{S_W}}{C_W + (BQ_V)_T} \right) = RI \cdot \left(\frac{C_W + \frac{(BQ_V)_C}{S_W}}{C_W + (BQ_V)_C} \right) \cdot \left(\frac{C_m + \frac{C_m \cdot (BQ_V)_m}{C_W \cdot S_W}}{C_m + \frac{C_m \cdot (BQ_V)_m}{C_W}} \right) \quad \text{eq. 11}$$

We have now successfully described Waxman and Smits¹⁾ correction for resistivity index as a function of two separate processes. The above equation converges as earlier described.

Boundaries are introduced in order to model a new empirical correlation. We have the following boundaries, which have to be consistent:

$$R_m \rightarrow \infty^+ \Rightarrow C_m \rightarrow 0 \quad \text{eq. 12}$$

$$R_m \rightarrow R_o \Rightarrow C_m \rightarrow C_o \quad \text{eq. 13}$$

Further, we have derived C_m for 100 % water saturation. We assume therefore that C_m has to be scaled with the respect to saturation. The following boundary has to be consistent, for a new correction term F, in order to be valid for clean sand, shaly sand, and sand with matrix conductivity:

$$C_m \rightarrow 0 \Rightarrow F \rightarrow 1 \quad \text{eq. 14}$$

The new correction term based on boundaries has to be dimensionless, in order not to disturb the derived Waxman and Smits¹⁾ approach.

If we summarize, we propose the following correction term based on boundaries:

$$F = \frac{1}{1 - \left(\frac{C_m}{C_W \cdot S_W} \right)} = \left(1 - \frac{C_m}{C_W \cdot S_W} \right)^{-1} \quad \text{eq. 15}$$

Finally, the new resistivity correction model is defined as follows:

$$RI^k = RI \cdot \left(\frac{C_w + \frac{(BQ_v)_c}{S_w}}{C_w + (BQ_v)_c} \right) \cdot \left(\frac{C_m + \frac{C_m \cdot (BQ_v)_m}{C_w \cdot S_w}}{C_m + \frac{C_m \cdot (BQ_v)_m}{C_w}} \right) \cdot \left(1 - \left(\frac{C_m}{C_w \cdot S_w} \right) \right)^{-1} \quad \text{eq. 16}$$

Results

Corrected petrophysical data, using eq. 16 are presented in Table 3 and Figure 3.

Reservoir Unit	n	S _{wi}	(BQ _v) _c	C _m	(BQ _v) _m	n ^k
	200 bar 81°C	200 bar 81°C (frac.)	200 bar 30 °C (Ωm) ⁻¹	200 bar 30 °C (Ωm) ⁻¹	200 bar 30 °C (Ωm) ⁻¹	200 bar 81 °C
Upper section	2.12	0.114	0.159	0.000	0.001	2.22
	1.82	0.105	0.231	0.000	0.004	1.95
Lower section	1.36	0.476	0.697	0.088	1.394	1.86
	0.49	0.478	0.538	0.612	12.617	1.78
	1.35	0.248	0.455	0.040	1.195	1.82
	1.41	0.432	0.743	0.014	0.918	1.80

Table 3 Corrected petrophysical properties.

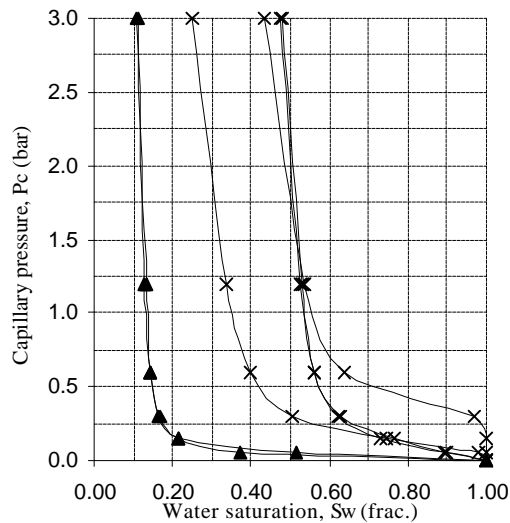


Figure 1: Capillary pressure versus water saturation.

Δ: Core plugs with normal resistivities.

X: Core plugs with earlier abnormal resistivities.

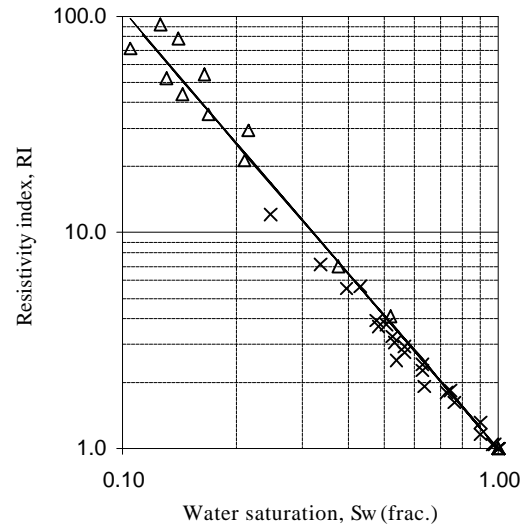


Figure 3: Corrected resistivity data for the core samples.

Secondary log evaluation

A MRIL log was also run over the reservoir. The difference between the interpreted water saturation from the Sands analysis and the bound fluid measured by the MRIL, indicates that there is movable water in the lower section. This is in contradiction with the produced oil from the well test and results from special core analysis which indicate that the matrix itself is very conductive.

An attempt has been made to correct for this effect in lower section of the reservoir. It is assumed that both the matrix and the fluid acts as parallel resistors for the total resistivity measured by the log. The log resistivities were corrected by subtracting the matrix contribution from the total signal.

The corrected resistivity log increased the net pay for the bottom 8.5 meter zone from 1.2 to 3.6 meter and the average water saturation dropped from 50 % to 35 % over the net pay interval.

Two CPI logs are presented to show graphically the difference between the two saturation profiles.

Conclusions

An empirical equation has been developed to correct resistivity data from core plugs.

The equation can be used for both clean sand, shaly sand and sand containing conductive minerals.

Secondary log evaluation, using the new method for resistivity correction, show a increase in net-pay for the reservoir, this in line with the obtained well test data.

The new correction term, F, has been tested on cleaned, 100% water saturated, core plugs. Further work is preferable to verify possible effects of wetting conditions on the correction term. There is therefor a potential for further improvement of the derived model.

The new correction term is dependent of good quality CEC data. In cases where matrix conductivity is a major problem, the quality of CEC data should therefor be verified by comparing CEC data with C_oC_w data for core plugs without matrix influence.

A detailed description of matrix conductivity versus depth from core data is essential in well log interpretation of reservoirs containing conductive minerals.

Nomenclature

Symbol	Description	Units
K_L	Klinkenberg corrected gas permeability	mD
F	Porosity	frac.
GD	Grain density	g/cm^3
n	Saturation exponent	
n^*	Waxman and Smits ¹⁾ corrected saturation exponent	
n^k	New method corrected saturation exponent	
S_{wi}	Irreducible water saturation	frac.
S_w	Water saturation	frac.
C_w	Conductivity of simulated formation water	$(\Omega m)^{-1}$
C_o	Conductivity of water saturated core plug	$(\Omega m)^{-1}$
C_m	Conductivity of matrix	$(\Omega m)^{-1}$
Q_v	Concentration of clay exchange cations	(meq/cm^3)
B	Conductance associated with each cations	$((\Omega m)^{-1}) * (meq/cm^3)$
$(BQ_v)_T$	Total measured BQV from $C_o C_w$ data	$(\Omega m)^{-1}$
$(BQ_v)_C$	Part of BQ_v related to clay activity	$(\Omega m)^{-1}$
$(BQ_v)_m$	Part of BQ_v related to matrix activity	$(\Omega m)^{-1}$
CEC	Cation exchange capacity	meq/100 g
R_o	Resistivity of water saturated core plug	Ω
R_m	Resistivity of matrix	Ω
FF	Formation resistivity factor	
FF^*	Corrected resistivity factor	
RI	Resistivity index	
RI^*	Waxman and Smits ¹⁾ corrected resistivity index	
RI^k	New method corrected resistivity index	
K_m	Matrix correction term	
K_C	Clay correction term	
F	New correction term for resistivity	
CPI	Computer processed interpretation	

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