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Calculation of Saturation Exponent from Water Relative Permeability Curves of Reservoir Rocks

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ABSTRACT

Saturation exponent is the most important and fundamental concept in considering the electrical properties of the reservoir rocks. It is a dimension less empirical parameter that is determined experimentally from core plugs. This parameter is important in investigation of hydrocarbon saturation of the oil reservoirs. The value of the saturation exponent depends on the wetting properties of the rock.

Laboratory methods of determining saturation require measurements of electrical resistivities of the rock at partial saturation. In these measurements, saturation anomalies or end effect can be ascertained. Experimental results show side discordance and it is known that difficulties are encountered which result from a lack of electrical contact between the electrode rings and the fluid network in the core pore space.

Based on the analogy between the electrical and physical properties of the reservoir rocks this paper presents a simple correlation for the estimation of the saturation exponents from water relative permeability curves that are widely available.

Comparisons between values of saturation exponent obtained experimentally and the resultant correlation of the present work have shown a good agreement for most of the samples.

INTRODUCTION

The reservoir rocks with exception of certain clay minerals, are made up of minerals which are non-conductors of electricity. Sedimentary rocks are conductors of electricity when their inter connected void spaces contain electrical conductive fluids namely formation water. When oil and gas which are non-conductors of electricity, are present within the porous rock together with a certain amount of saline formation water, its resistivity (Rt) is higher than that of fully saturated formation water (Ro), since there is less available volume of water for the flow of electric current. The available volume of water to current flow is designated as its saturation in the pore space (Sw). Resistivity of a partially water saturated rock depends not only on the value of Sw but also on its distribution within the pore space. The fluid-phase distribution within the rock depends on the wetting properties of the rock and the direction in which it was established (drainage or imbibition). The general accepted formula which relates water saturation and resistivity ratio (Rt/Ro) is that of Archie (1942) which may be written as:

$$Sw^{-n} = (Rt/Ro) = I \qquad ....(1)$$

where n is the saturation exponent and I is resistivity index.

The saturation exponent, n, is a dimension less empirical parameter that is determined experimentally from core plugs (Dunlop, 1949; Birks, 1954). The value of n depends on the formation but usually has a value of about 2 for water wet formations and cleaned water-wet cores. Mungon & Moore (1968) have pointed out that the saturation exponent equation makes three implicit assumptions: (1)

NOMENCLATURE

Sw = water saturation, present
Sro = residual oil saturation, percent
Siw = irreducible water saturation, percent
n = saturation exponent
I = resistivity index
Ro = resistivity of fully water saturated samples, ohm-cm
Rt = resistivity of partially water saturated samples, ohm-cm
Rw = brine resistivity, ohm-cm
C = current, amp
E = voltage drop, volts
r = resistance, ohms
A = cross sectional area cm^2
L = length of the flow path, cm
Q = flow rate, cm^3/sec
μ = water viscosity Cps
P = pressure drop, atm
K = permeability, darcy
Krw, Ke, Ka = relative, effective and absolute permeability respectively

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the saturation/resistivity relation is unique, so that only one resistivity will ever be measured at a given saturation; (2) n is constant for a given porous medium; (3) all the brine contributes to the flow of electric current. It has been shown that these assumptions are valid only when both the reservoir and core are strongly water-wet, because n depends on the distribution of the conducting phase in the porous medium and therefore depends on the wettability. If the wettability is altered, it changes distribution of the fluids and changes lengths and cross-sectional areas of the conductive paths, which in turn changes the resistivity. Hence, the saturation exponent is non-unique when the wettability is altered because different resistivities can be measured at the same saturation. The experiments show that n can be much higher in oil wet than in water wet rocks.

EFFECT OF ROCK WETTABILITY ON SATURATION EXPONENT

Consider a water-wet system initially at a high brine saturation. The brine is located in the small pores and as a thin layer on the rock pores. All the water is continuous and can conduct current. As the water saturation is lowered to the irreducible water saturation (Siw) essentially all of the brine in a water-wet system remains continuous and conductive, allowing the saturation exponent to remain about 2. This continuity at all saturation above the Siw implies that most of the increase in resistivity is caused by the decrease in cross-sectional area available for conduction and not by increase in the path length or brine trapping. In most oil wet systems, the oil is located in the small pores and on the rock surfaces, while the brine is located in the centre of the larger pores. At high brine saturation, the brine is continuous, just as it is in a water wet system, even though its location is different. For this situation, the resistivity/saturation relation behaves as it does in the water-wet cores, with n around 2. In contrast to the water-wet system, however, as the brine saturation decreases, a portion of the brine no longer contributes to the current flow. The saturation exponent increases as soon as the brine saturation is decreased, while in some cores the brine saturation must be reduced to about 35% before n increases (Mungan & Moore, 1968). At a very low water saturation ($Sw = 35\%$), large values of the saturation exponent ($n > 10$) can occur.

The factor can cause the resistivity and hence n to rise more rapidly as compared with the water-wet cases, the trapping of a portion of the brine by oil and the formation of dendrites or fingers of brine. These two factors decrease the cross-sectional area and increase the length of the conducting paths, thereby increasing electrical resistivity. The isolated brine is surrounded by non-conducting oil and can not contribute to the current flow. As the brine saturation is reduced, the electrical resistivity will also be increased because some of the brine will be located in the pseudo-deadend pores, also known as fingers. These fingers consist of brine that is connected to the continuous brine in only one location. The brine can not conduct electricity because of the oil/water interfaces in the remainder of the pore throats, so the length of the conducting paths is increased. The disconnected brine did not conduct electrical current because it is completely surrounded by the insulating wetting phase (oil). Finally it is concluded that:

1. The saturation exponent is almost independent of the rock wettability when the brine saturation is sufficiently high and the brine is continuous.
2. The saturation exponent equation is not valid at low water saturation in an oil-wet rock.
3. Wettability effects become very important when the brine saturation is lowered. In general, essentially all the brine in a uniformly water-wet core remains continuous and electrically conducting as the brine saturation is lowered to the irreducible saturation.

LABORATORY METHODS FOR DETERMINING SATURATION EXPONENTS

Laboratory methods for determining saturation exponents require measurement of electrical conductivity of a rock at partial saturation, this saturation corresponds to the same fluid distribution as in situ. Many methods have been proposed for measuring n for a system, such as Capillary Pressure Cell method (Dunlop, 1949) and Water Evaporation method (Birks, 1954).

The experimental systems used can be divided into three types: (1) Uniform Wetting System, (2) Reservoir Cores which may or may not have uniform wettability, and (3) Fractional and Mixed Wettability System.

In these laboratory measurements, saturation anomalies or end effect can be ascertained. Results show wide discordance. Also there is a possible loss in saturation during measurements which can be ascertained (Pirson, 1958).

Based on the analogy between the electrical and the physical properties of the rock, this study provides a simple correlation for estimating the saturation exponent from the water relative permeability curves that are widely available in core laboratories. Water relative permeability curves were chosen for the analogy by the resistivity index of the reservoir rocks for the following reasons:

1. There is no hysteresis in the water relative permeability (William, 1987).

2. The wetting phase relative permeability was not dependent on the prior saturation history or direction of displacement (Craig, 1971).

3. Although the absolute permeability is not affected by wettability, the effective oil permeability at (Siw) decreases as a core becomes more oil wet (William, 1987).

4. In addition, water relative permeabilities are very similar for both two and three relative permeability measurements at a given wetting phase saturation (Donaldson, 1981).

Determination of the Saturation Exponent Basis for the Analogy

The basis for the analogy by which an interpretation of electrical data may be made to serve in study of oil fields is that the flow of oil in the formation expressed by Darcy's Law is analogous to the flow of electricity expressed by Ohm's Law. Darcy's Law states that the velocity of fluid flow is proportional to the pressure drop per unit length along the line of flow, and Ohm's Law expresses the current as directly proportional to the voltage drop per unit length. In brief, the pressure distribution in the oil sand and voltage distribution in the same medium are identical (William, 1981). The relationship between the electrical properties and physical properties of the reservoir rocks is complex but can be illustrated by the following developments.

Ohm's Law is commonly written as:

$$C = \frac{E}{r} = \frac{A}{RwL} \cdot E = A \cdot \frac{1}{Rw} \cdot \frac{E}{L} \quad .....(2)$$

This expression is analogous to the following Darcy's Law for the linear flow of fluids.

$$Q = A \frac{K}{\mu} \cdot \frac{\Delta P}{L} \quad ....(3)$$

Note that

$$Q \sim C, \quad \frac{\Delta P}{L} \sim \frac{E}{L} \quad \text{and} \quad \frac{K}{\mu} \sim \frac{1}{Rw} \quad ......(4)$$

Considering that the brine viscosity of experimental conditions is nearly unity, according to the basis of analogy, the reciprocal of resistivity is analogous to the rock permeability,

$$K \sim \frac{1}{Rw}$$

If the porous medium was fully saturated with the brine of resistivity Rw, its resistivity will be greater than Rw as the porous medium is non-conductive and will be equal to Ro. For this condition of saturation Sw is equal to 100%, the rock permeability is defined as the permeability Ka and is analogous to the reciprocal of Ro i.e.

$$Ka \sim \frac{1}{Ro} \quad ....(5)$$

Now if the porous medium contains both water and hydrocarbons, ($Sw = 100\%$), the water still remains the only conductor and the resistivity of this partially water saturated rock becomes Rt which is greater than Ro. This resistivity will be analogous to the reciprocal of the permeability at this partial saturation condition which is known as the effective permeability,

$$Ke \sim \frac{1}{Rt} \quad ....(6)$$

As defined in literature, the relative permeability is the ratio of the effective permeability to the absolute permeability, according to the relations (5) and (6), it is, by analogy equal to the resistivity ratio and can be expressed symbolically as:

$$K_{rw} = \frac{Ke}{Ka} = \frac{Ro}{Rt} \quad ....(7)$$

However from equations (1) and (7)

$$Sw^{-n} = \frac{1}{Krw} \quad ....(8)$$

This equation can be put into the form:

$$-n \log(Sw) = \log(1/Krw) \quad ....(9)$$

This equation shows a straight line on log paper between (Sw) and (1/Krw) where the saturation exponent (n) is the slope. Whether the value of n in equation (8) is identical to that obtained by Archie formula in equation (1) remains to be proved.

Table 1. Basic Data from a Core Sample from Well RB-AI (EE-85 = 4). [Sample No.12B, Formation: N. SST-UNIT IIP, Porosity: 11.5%, Air Permeability: 40 md, Oil Permeability: 29 md].

Sw	Kwr	1/Krw	Rt/Ro
0.216	0.000		0
0.271	0.169	5.917	
0.308	0.190	5.263	
0.342	0.210	4.762	
0.375	0.232	4.310	
0.381			3.43
0.395			3.17
0.439	0.281	3.559	
0.448			2.76
0.514	0.348	2.874	
0.529			2.15
0.569	0.401	2.494	
0.608	0.557	2.237	
0.638	0.488	2.049	
0.652	0.509	1.965	
0.693	0.552	1.812	
0.714			1.48
1.000			1.00

Table 2. Relative permeability data of core samples from Rasbandrana oil field.

Sample No.	(n) From Archie Formula	(n) From Relative Permeability Data
12 B	1.252	1.051
13 A	1.783	1.893
14 A	1.631	1.837
5 A	1.786	1.800
6 A	1.693	1.733
5 E - 5 D	1.879	2.007
9 E - 9 D	2.950	2.618
7 A	1.955	1.695
8 A	1.633	1.499
15 A	2.014	2.031
2 A	1.861	1.905
3 A	1.740	1.759
9 A	1.524	1.696

For comparing this relation with that of Archie, a data set of samples were used, Figure 1 through Figure 3 show a plot of (Rt/Ro) and (1/Krw) versus (Sw) for 13 core samples of Rasbandrana oil field. The basic data are present in Tables 1 and 2.

Comparison of the value of n obtained by the present correlation equation (8) as shown in Figure 4 shows good quantitative agreement with that obtained by using Archie formula in equation (1). It is evident from these figures that greatest deviations are present in the high water saturation regions (Sw > 50%). Reasons for this include:

1. For predicting Archie formula, the condition of fully saturated sample with water (Sw = 100%) has been attained, which is impossible to attain practically in case of relative permeability data where there is a value of the residual oil (Sro).

2. The presence of a significant part of the residual oil, trapped or located in dendrites, is considered as a part of the matrix, where it could not contribute to the conductivity and causes a high value of resistivity ratio Rt/Ro. Also this residual oil could not move through the porous medium causing very low oil permeability.

3. At the residual oil saturation the relative permeability to oil becomes zero and thus brine moves alone through the porous medium with a relative permeability analogous to the absolute permeability. In other words, the reciprocal of relative permeability of water at (Sro) is analogous to the resistivity ratio at the condition of the fully saturated samples with water (Sw = 100%).

To avoid these deviations due to the presence of the residual oil saturations, the slope of the straight line in the low water saturation region (Swl < 50%) have been taken into consideration for the present correlation.

Knowing that a large number of variables affect the oil saturation including wettability, viscosity ratio, saturation history, pore geometry and injection rate, a degree of this deviation must clearly result from the rock property variations. Finally, we concluded that within the limitations of deviations caused by sample peculiarities and presence of residual oil saturation, the new correlation should generally be good representation of the reservoir rock.

CONCLUSION

1. By using analogue between the fluid properties and the electrical properties of the reservoir rocks and fluids, it is possible to obtain solutions for complex problems of fluid flow.

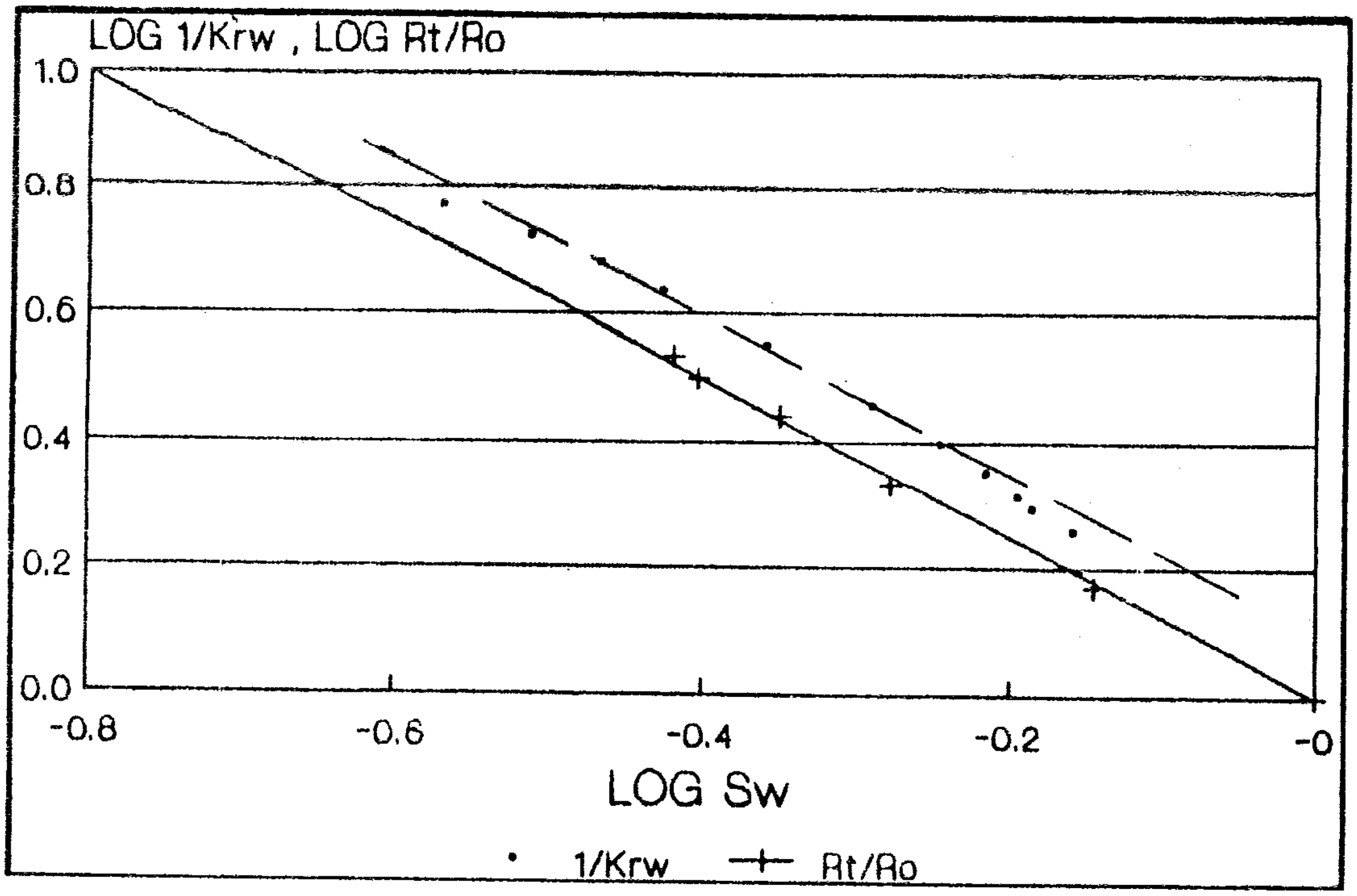

Figure 1— Log Sw vs. Log 1/Krw, Log Rt/Ro for sample no. 12 B.

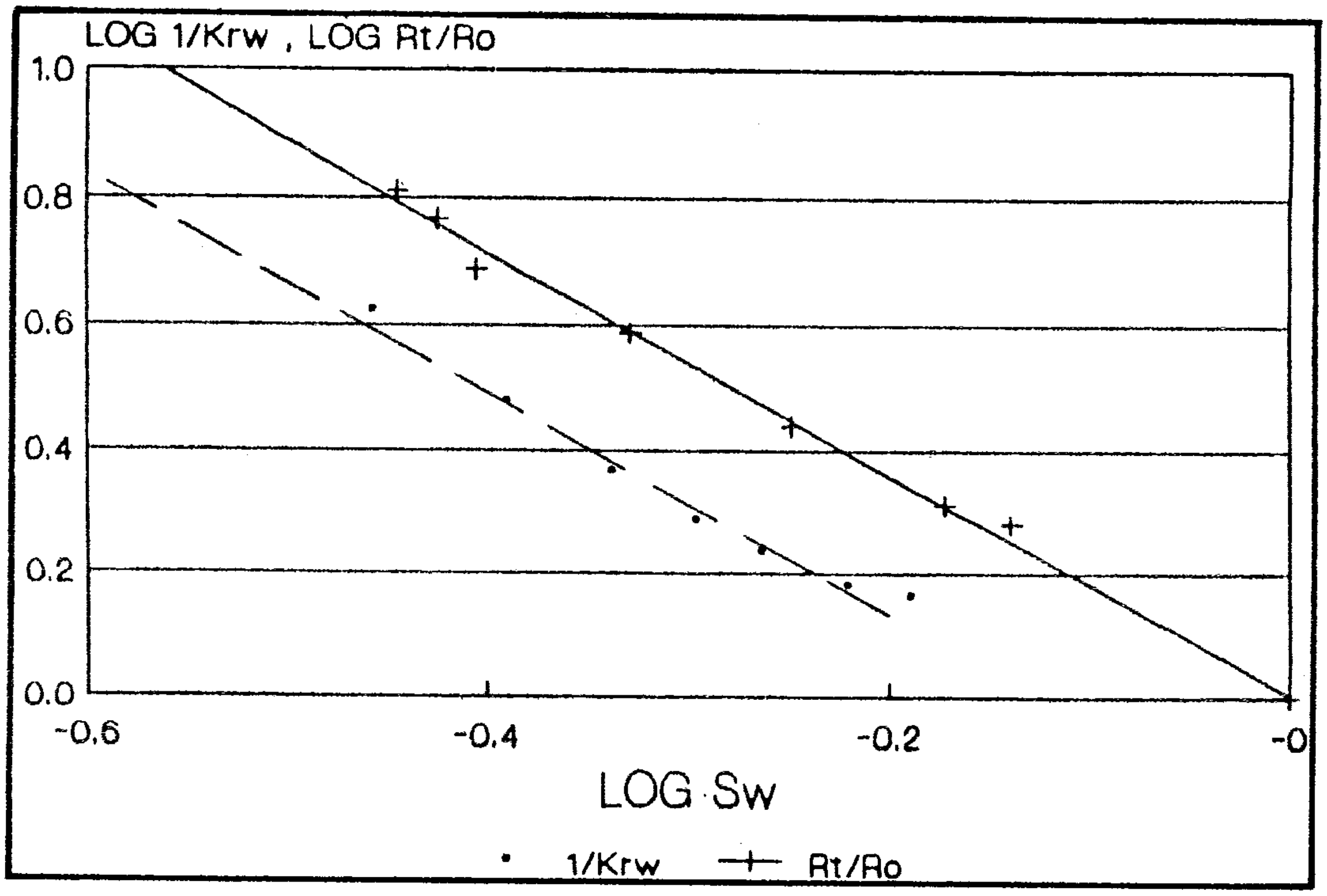

Figure 2— Log Sw vs. Log 1/Krw, Log Rt/Ro for sample no. 13 A.

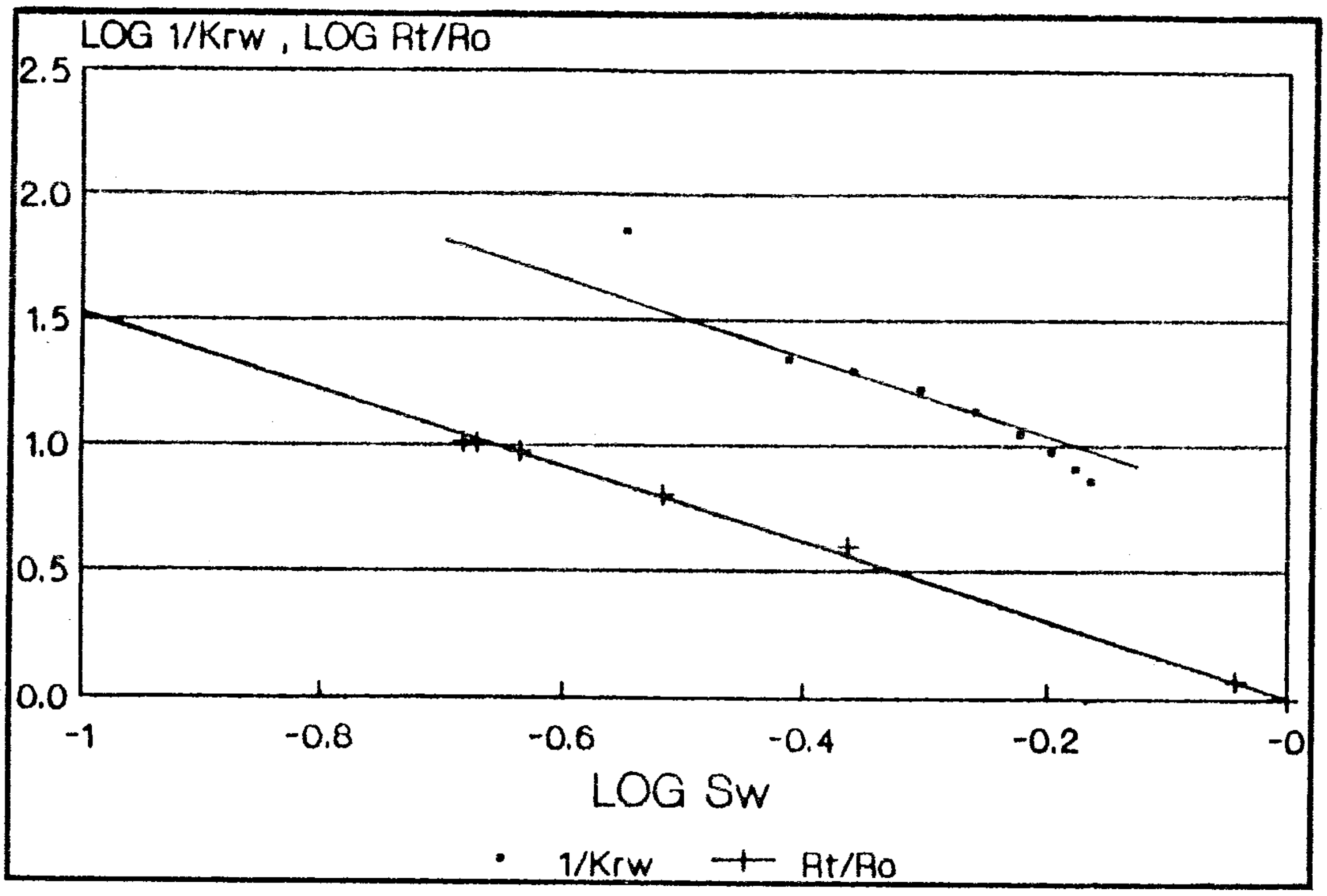

Figure 3— Log Sw vs. Log 1/Krw, Log Rt/Ro for sample No. 9 A.

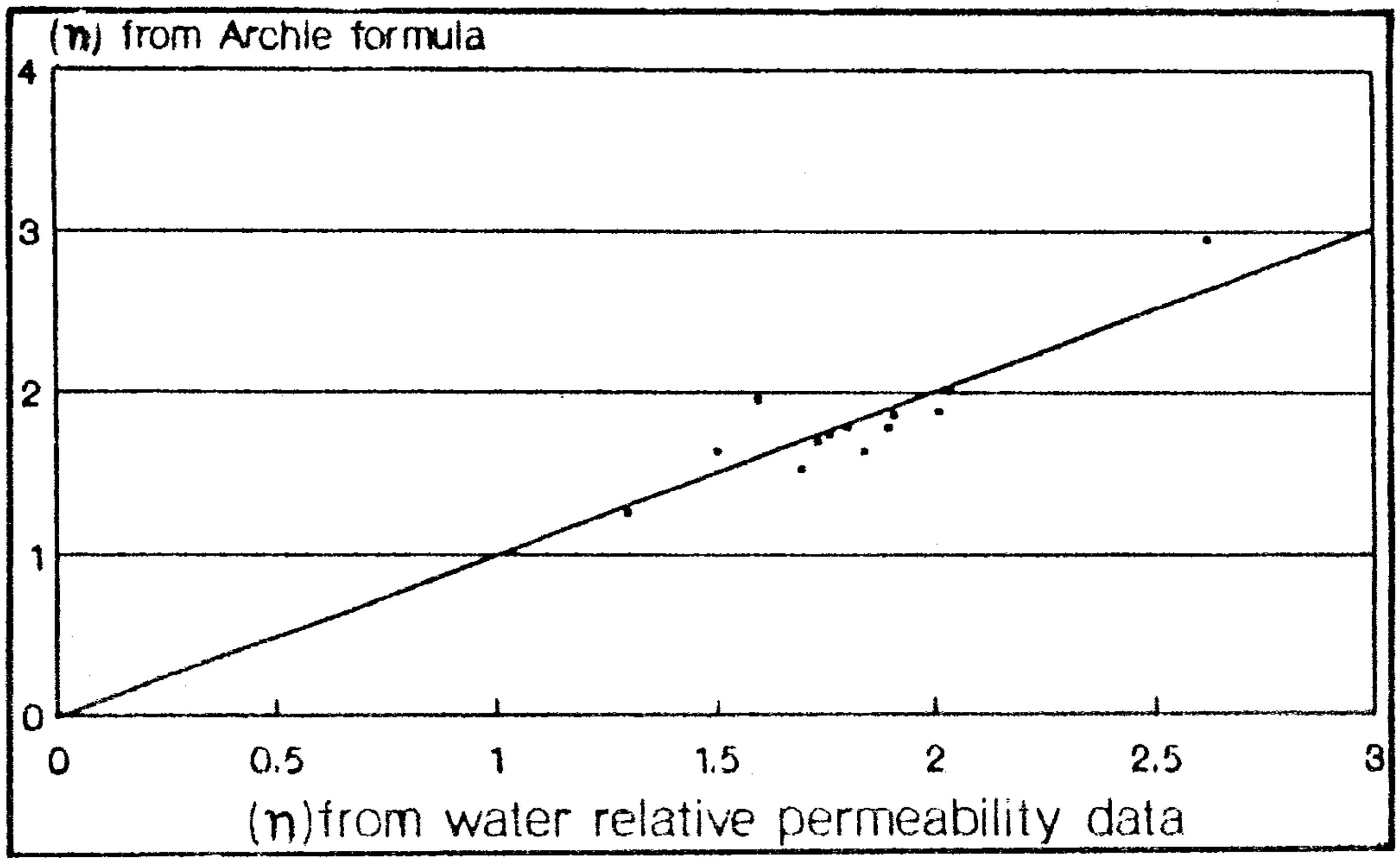

Figure 4— Comparison of saturation exponent (n) from Archie formula with that from water relative permeability data.

2. The resistivity ratio (Rt/Ro) by analogy equals to the reciprocal of the relative permeability of water (1/Krw).

3. A straight line relationship on log paper between (Sw) and (1/Krw) with a slope equal to the saturation exponent (n) similar to Archie formula, has been found.

4. Comparison of the value of (n) obtained by the present correlation with that obtained by Archie formula shows good quantitative agreement.

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