

Relative permeability, hysteresis and $I-S_w$ measurements on a carbonate prospect

N. van der Post, S.K. Masalmeh, J.G.C. Coenen, K.H. van der Gijp and J.G. Maas

Shell International Exploration and Production B.V.
Rijswijk
The Netherlands

Abstract

We present SCAL measurements on a high porosity Middle East carbonate reservoir. The cores are aged with crude, and relative permeability is measured using an X-ray steady state, a γ -ray steady state and the centrifuge technique. In the steady state we measured the primary imbibition and secondary drainage relative permeability curves of oil and water. Both resistivity and oil/water saturation can be measured along the core on different places, allowing the quantification of capillary end effects and its impact on resistivity. In the centrifuge we measured the imbibition oil relative permeability curve. The main points of interest are:

- Reconciling reservoir initial water saturation as obtained from logs and SCAL
- Wettability and relative permeability of aged samples
- Comparing $I-S_w$ measurements from the continuous injection technique with resistivity measurements done in the X-ray steady state.
- Hysteresis in relative permeability and $I-S_w$ between the imbibition and secondary drainage curves.

We will show that the hysteresis in relative permeability is typical for a mixed-wet sample. After aging the samples $I-S_w$ results show marginal hysteresis. For these mixed-wet samples we measured a high saturation exponent ($n = 3$) compared to $n=2.2$ measured in the continuous injection method on water-wet samples taken from the same formation.

Introduction

Well logs of this high porosity Middle East carbonate reservoir have shown anomalously high logged resistivity values of 2000 Ωm . Using previous resistivity index measurements, this led to the conclusion that the connate water saturation of the reservoir was about 1.5%. Apart from being unrealistically low, this is also in contradiction to SCAL measurements, which give connate water between 5% and 10%.

A project was therefore started to measure the resistivity index in a more realistic environment. From capillary pressure measurements, the reservoir is known to be mixed wet, and therefore the water wet continuous injection method which uses water and

kerosene, may not be correct. We have used a newly developed X-ray steady state apparatus to do the resistivity measurements. Pressure and voltage probes are placed in the sleeve surrounding the core, thereby allowing resistivity to be measured at different locations along the core. It will be shown that by doing this, a consistent data set can be obtained. Furthermore, it is shown that relative permeabilities as measured by the centrifuge and the steady state technique overlap, and that after aging the crude can be replaced by decane to speed up the measurements.

In this paper drainage refers to the process of oil displacing water experiment while imbibition refers to water displacing oil experiment regardless of wettability status of the samples.

Experimental setup

We have used the X-ray steady state setup as described in [1]. Some modifications in the set-up were necessary because of problems with stability of the X-ray signal; notably the stiffness of the construction appeared to be of key importance. After these modifications took place, it was found to be easy to measure water and crude saturations with accuracy better than 2% by scanning some 15 seconds. The X-ray source and detector are mounted on a stepper motor, thus making it possible to monitor the saturation along the core. As will be shown later, this saturation measurement is necessary to obtain consistent results with e.g. the resistivity measurement. A complete scan -- taking 20 saturation points on the core and performing a calibration measurement -- takes about 10 minutes. For comparison, one relative permeability measurement has been done using our conventional γ ray steady state set up.

The core holder is of a water and crude injection type, with a single producer. Special features are the two pressure probes along the core, and a method to measure in situ resistivity. The latter is done as follows (Fig. 1): a platinum mesh at the top and bottom of the core are used as current contacts. The pressure probes and two other probes can be used as voltage probes. A 4-point measurement is then done, removing contact resistances. Since pressure and separate voltage probes are used to measure the voltage along the core, this allows to measure the resistivity on different places on the core, cf. Fig. 1.

It was further checked that the used brine does not induce important current leaks to the electrical ground, that is, not in the resistance range explored here (R_{core} between 50Ω and $25k\Omega$). With a typical brine resistivity of $\rho_{brine}=0.05\Omega m$, a brine lead line of length 2m and diameter 0.5mm, the leaking resistance is expected to be of the order of $500 k\Omega$, indeed much larger than the core resistances encountered in the present experiments.

The present set-up will later this year be upgraded with water and oil wet pressure probes, allowing to measure the capillary pressure *together* with the relative permeability and the resistivity.

Sample preparation

The used carbonate material was relatively friable, but still allowed cleaning by using an azeotropic mixture. Permeabilities were around 5mD and porosities 40%. The cores were then desaturated with crude in the centrifuge. It was observed that maximum accelerations were of the order of 30000 m/s^2 , above this the material collapsed. The cores were then aged for a month at elevated pressures and temperatures. The centrifuge measurements described below have been performed using the crude, however for the steady state measurements this was not possible. Reason is that the centrifuge can be operated at elevated temperatures -- in the present experiment at 60C -- at which the crude has a 'workable' viscosity of 4cP. The steady state is however preferred to be operated at room temperature (19C), and then the viscosity of the crude is 16cP. Since this increases the characteristic experimental time considerably, it was decided to wash out the crude with decane. Subsequently, decane and brine are used to perform the measurements.

Given the low permeability, high porosity nature of the material, washing out of the crude is not trivial. It was found that best results are obtained by heating the steady state to 60C, flooding 1 hour with decane at 1 ml/min, stopping 2 hours, flooding 1 hour, etc. After several days no visible coloring of the affluent was observed anymore, and therefore the washing out was considered to be successful. It should be noted; however, that during azeotropic cleaning after the experiment, some colored affluent could still be produced. It is not expected that the leaving behind of small amounts of crude affects the measurements considerably, and this expectation was indeed proved by comparing the centrifuge (crude) and steady state (decane) measurements, as described below.

Before installing the core into the steady state setup, first the resistance was measured by using a standard clamp device (core clamped between probes and a DC resistance measurement). This reading was successfully compared to the first reading of the current and voltage probes. Sometimes the voltage probe did not seem to make electrical contact with the core. This can be understood by knowing the core was submersed in non-conducting crude before sample preparation, which may form an isolating film on the core. Two experimental tricks were used to circumvent this problem. First, the sleeve pressure (~20bar) could be removed and re-installed. This 'breathing' of the sleeve induces redistribution of the fluids around the core, and could result in establishing electrical connectivity. When this method was without success, a tiny amount of brine (typically 0.03% of the core pore volume) was supplied to the core. Since the core will be in the water-wet branch of its capillary pressure, it will draw-in the water and redistribute over the core. This always brought correct electrical connectivity to the pressure probes. After this, decane was injected again to bring the core back to its initial water saturation, from which it was deviated a couple of percent by the latter trick.

Relative permeability measurements

After ageing, relative permeabilities were measured with the following equipment on the following cores:

- Steady state: Oil and water relative permeability on sample 1 in first imbibition and secondary drainage. Fluids are brine and decane. X-ray steady state.
- Steady state: Oil and water relative permeability on sample 2 in first imbibition. Fluids are brine and decane. Conventional γ -ray steady state.
- Centrifuge: Oil relative permeability on samples 3 and 4 using brine and crude.

In the steady state, high viscous pressures were used compared to the capillary entry pressure ~ 0.2 bar. This way, the capillary end effect is expected to be suppressed. This was indeed found when the saturation profiles were measured. An example of this can be observed in Fig. 2, where saturation profiles are given for different fractional flow rates to water. It can be seen that initially – that is during the decane flood at connate water (FFW=0) -- a considerable saturation gradient is present in the sample. After flowing with nonzero fractional flows the gradient disappears. Note that around position 30, a voltage probe is hindering the X-rays, leading to inaccurate saturation readings.

In Figs 3a and 3b the relative permeabilities are compared as measured on samples 1 and 2 in the X-ray and γ -ray steady state, respectively.

The centrifuge measurements are interpreted using Shell's in house numerical simulator (MoReS). A typical fit of the production curve can be observed in Fig. 4. It can be observed that one of the merits of performing the analysis with a numerical simulator is that after 4 days of experiment, the measured residual oil saturation S_{or} from the average saturation is 0.18, whereas the fitted S_{or} was 0.13. The latter is more in line with the steady state experiments ($S_{or} = 0.12$). It maybe surprising that the steady state gives lower residual oil saturation than the centrifuge. However, in this case we could not apply high gravity forces in the centrifuge because the samples are fragile. In the steady state the samples were mounted in a sleeve and a high confining pressure was applied to prevent plugs from collapsing during the experiment. This way we could apply high viscous pressure (more than 8 bars in the steady state compared to less than 3 bars in the centrifuge) and got lower residual oil where the capillary end effect was suppressed.

In Fig. 5 the results are given of the centrifuge measurements, where the crude relative permeability was measured. The oil relative permeability measured with crude is here compared to the oil relative permeability as decane. It was not possible to measure the water relative permeability in the centrifuge, since the invading phase (crude) has a much larger viscosity than the displaced phase. Even numerical evaluation of the measurement results does not lead to accurate water relperm determination.

Hysteresis was measured on sample 1 with the secondary drainage relative permeability. This can be observed in Fig. 6.

Resistivity measurements

While logging the wells of this field, it was found that very high resistivities were measured, up to 2000 Ωm . Given the brine resistivity at reservoir temperature of 0.2 Ωm , this results in a resistivity index of 10000. To map this value to a connate water saturation, I-Sw measurements were performed using the continuous injection technique. Some examples of this measurement can be observed in Fig. 7. The average saturation exponent of these experiments was around $n=2.2$. Using this n value together with the measured $I=10000$ down hole, a connate water saturation of 1.5% is calculated. Problem with this value is that it is not consistent with either continuous injection, centrifuge or steady state measurements. Therefore it was decided to measure the resistivity also on aged samples, in the X-ray steady state.

The voltage drop over the top added to the voltage drop over the bottom should be equal to the voltage drop between the platinum electrodes. This is exactly true when single phase brine is present in the core, but as soon as two phases are present, the addition can be off by up to 10%. We do not have an explanation for the latter effect, but note that these inaccuracies do not affect our conclusions. The resistivity index measurements are very sensitive to the water saturation, especially at low water saturations. It is therefore imperative that a resistivity measurement over e.g. the top part of the core is accompanied by a saturation measurement at that position. If this is not done, the measurements seem to be very noisy, whereas they are not noisy, but just wrongly interpreted. This makes saturation monitoring over the whole core of key importance.

The results from the I-Sw measurement on aged cores are quite different from the continuous injection results measured on water-wet samples. First of all, it was checked whether the resistivity measurement on different places on the core gives consistent results. Fig. 8 shows the results: indeed excellent consistency was found. The figure presents measurements on sample 5, on different locations of the core, compared to the measured $n=2.2$ of the non-aged continuous injection method. To confirm the above results, in subsequent samples 6 and 7, focus has been given to the resistivity index at very low water saturations. This value was consistently found to be about ~ 1000 at water saturations of 10%. Further note that the high resistivity values at these low water saturations are not an experimental artifact of the steady state setup, since these values could be reproduced using a conventional clamp device as used in the continuous injection method.

Discussion

From the above measurements, we make the following observations:

1. Fig. 2: Except for the zero fractional flow for water, no end effects are present in the steady state measurements. The end effect at the beginning of the first imbibition is most probably due to a relatively small (0.4 bar) pressure drop compared to typical pressure drops of 5 bar in the nonzero FFW's.

1. Fig. 3: The spread in relative permeability for the present core material is very limited. The accuracy of the measurements is high both in the γ and X-ray set-up
3. Fig. 4&5: When correctly interpreted the measured relative permeability is independent of the fluid used (crude or decane in an aged plug) or the experimental technique (steady state or centrifuge). In this case the interpretation of the steady state has been done using Darcy's law as the capillary end effect was suppressed by applying high pressure and using multiple pressure ports. The centrifuge data was interpreted using numerical simulation.
4. The resistivity measurements on un-aged core plugs with the continuous injection lead to saturation exponents of around $n=2.2$. Measurements on aged plugs have consistently (in 3 plugs) led to $n=3$. Given the $I = 10000$ measured in the field, the latter saturation exponent leads to a connate water saturation of around 5%. This can be consistent with the present measurements, where it was possible to attain water saturations as low as $\sim 7\%$. Lower water saturations were not possible because the plugs were desaturated in the centrifuge, and higher accelerations destroyed the core plugs. It is known from literature [4,5] that n may increase when the core is aged, and the present observations support this.
5. For the relative permeabilities, there is a clear hysteresis between the primary imbibition and secondary drainage curves for both oil and water. As shown in the figure the secondary drainage oil relative permeability is higher than the primary imbibition while for water it is lower. To explain this behavior we have to understand the filling sequence during drainage and imbibition experiments. In primary drainage oil enters the big pores first because they have the lowest entry pressure. During the aging time some of the oil contacted parts of the rock become oil-wet. The higher the initial oil saturation the higher the fraction of pores that are rendered oil-wet [2]. In primary imbibition water starts to displace oil from the small water-wet pores and big oil-wet pores. Therefore, for a given water saturation water occupies more big pores during primary imbibition than during primary drainage [3]. Thus water relative permeability is higher in primary imbibition than during primary drainage at a given water saturation. For oil, using the same reasoning, the relative permeability in the primary imbibition is lower than in the primary drainage. In the secondary drainage, oil starts to displace water from the small oil-wet pores and big water-wet pores. Therefore, at a given water saturation oil will occupy more big pores than in primary imbibition but less big pores than in primary drainage. Consequently, the secondary drainage oil relative permeability in secondary drainage is higher than in the primary imbibition but lower than in the primary drainage. Conversely, water relative permeability is lower in secondary drainage than primary imbibition but higher than that in primary drainage. The primary drainage data was not measured for the example shown in figure 6, however the data measured on other samples agree with the model discussed above.
6. For the $I-S_w$ there is hardly any hysteresis obtained between the first imbibition and secondary drainage data. This observation is in agreement with the data reported in [4] where no hysteresis was observed between primary imbibition and secondary drainage tests for either water-wet or oil-wet samples.

Conclusions

1. We have developed a reliable and accurate X-ray steady state apparatus that can measure relative permeability and resistivity simultaneously.
2. Relative permeabilities as measured with steady state and centrifuge reproduce very well.
3. It was observed that resistivity values from the well logs cannot be reconciled with measured connate water saturations when the saturation exponent was used as measured on non-aged plugs. This led to $n=2.2$, resulting in connate water saturations of only 1.5%. When measuring on aged plugs, the saturation exponent is consistently higher, around $n=3$. This leads to a connate water saturation of 5%, internally consistent with SCAL.
4. Hysteresis effects are present for the relative permeabilities: in secondary drainage the oil relative permeability is higher, and the water relative permeability is lower than in first imbibition. The hysteresis in resistivity is much smaller.

Acknowledgement

We like to thank management of Shell Technology Exploration and Production in Rijswijk for permission to publish this paper.

References

- [1] Coenen JGC and Koornneef P, "State of the art X-ray steady state apparatus for advanced core flow studies", (1998) SCA9853.
- [2] Salathiel R.A., "Oil Recovery by Surface Film Drainage in Mixed-Wettability Rocks", J. Pet. Tech., (Oct. 1973) 1216-1224.
- [3] Jerauld G.R., "General Three-Phase Relative Permeability Model for Purdhoie Bay", SPE 36178, (1996) 37-48.
- [4] Elashahab B.M., Jing X.D. and Archer J.S., "Resistivity Index and Capillary Pressure Hysteresis for Rock Samples of Different Wettability Characteristics", SPE 29888, (1995) 519-529.
- [5] Longeron D.G., Argaud, M.J., and Feraud, J.P., "Effect of Overburden Pressure and the Nature and Microscopic Distribution of Fluids on Electrical Properties of Samples, SPE Formation Evaluation (June 1989), p.194-202. "

		units	#1	#2	#3	#4
setup			XSS	XSS	CEN	CEN
Air permeability	<i>K_{air}</i>	[mD]	14	14	11	26
Brine permeability	<i>K_{brine}</i>	[mD]	14	14	x	x
Porosity	<i>Φ</i>		0.426	0.324	0.383	0.428
Sample length	<i>l</i>	[cm]	4.00	4.00	4.48	4.48
Sample diameter	<i>d</i>	[cm]	2.51	2.51	3.77	3.77
Pore volume	<i>PV</i>	[cm ³]	8.43	6.41	19.15	21.40
Connate water sat.	<i>Sc_w</i>		0.16	0.21	0.26	0.18
Residual oil sat.	<i>S_{or}</i>		0.12	0.16	0.08	0.08

Table 1: Core properties of core #1-#4. XSS means X-ray steady state, CEN denotes centrifuge measurement.

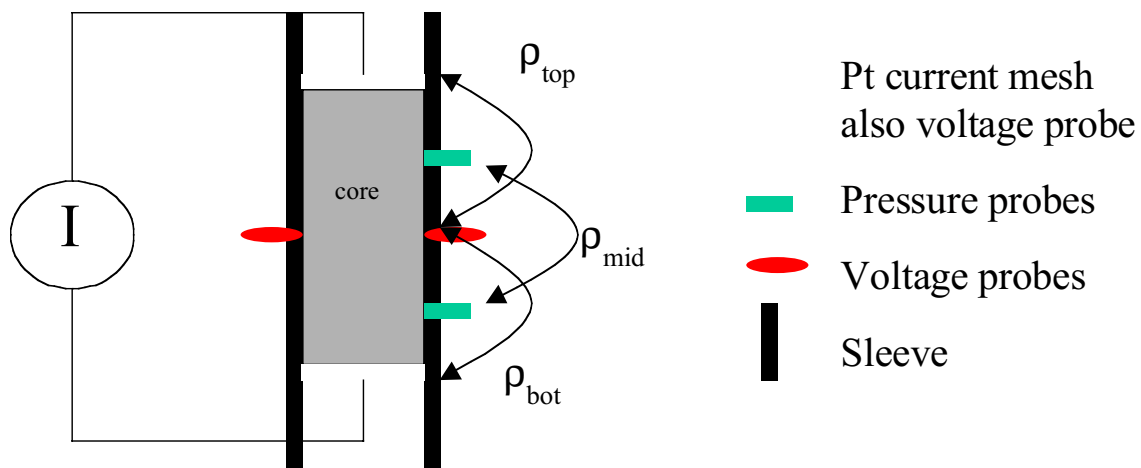


Figure 1: schematic representation of the core holder used in the X-ray steady state. A platinum mesh is used as current injector and drain, and pressure and separate voltage probes are used to measure the voltage along the core. This allows measuring the resistivity on different places on the core.

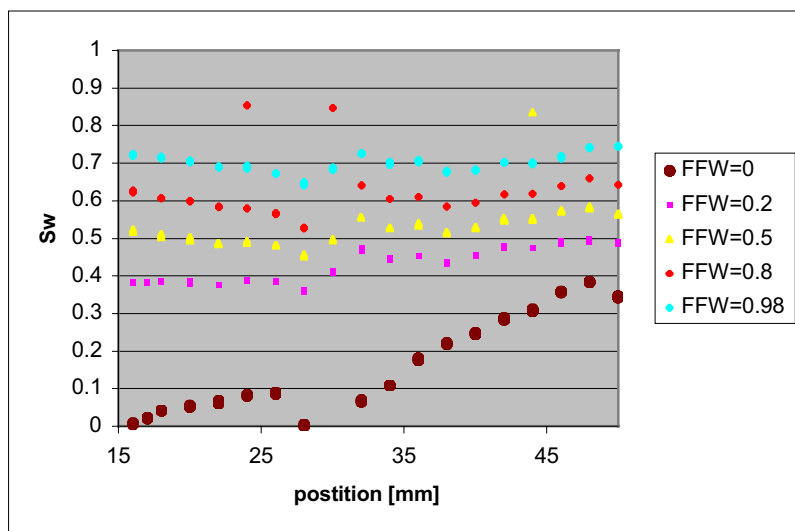


Figure 2: saturation profiles along the core. It can be observed that initially during the decane flood at connate water (fractional flow for water $FFW=0$) a considerable end effect was present. This is absent during other fractional flows. Around position 30 a resistance probe is present, making the saturation measurement inaccurate.

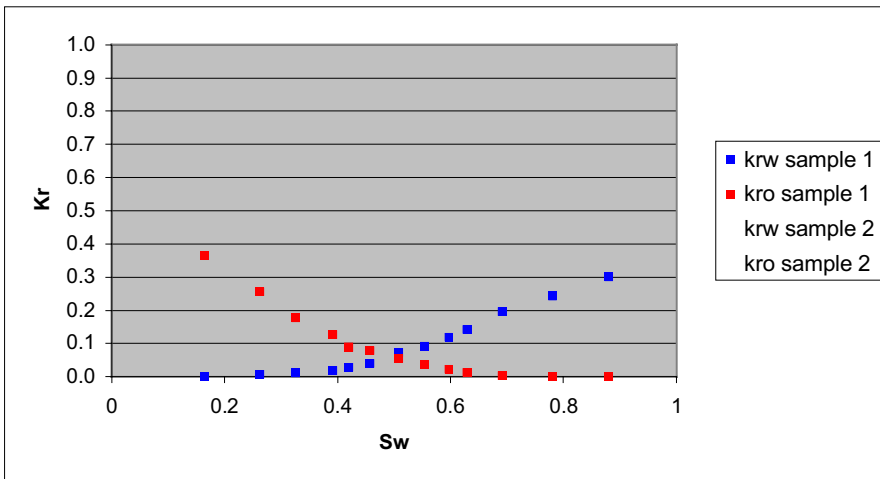


Figure 3a: First imbibition relative permeabilities of crude (k_{ro}) and brine (k_{rw}) as measured with the X-ray and γ ray steady state on sample 1 and 2, respectively

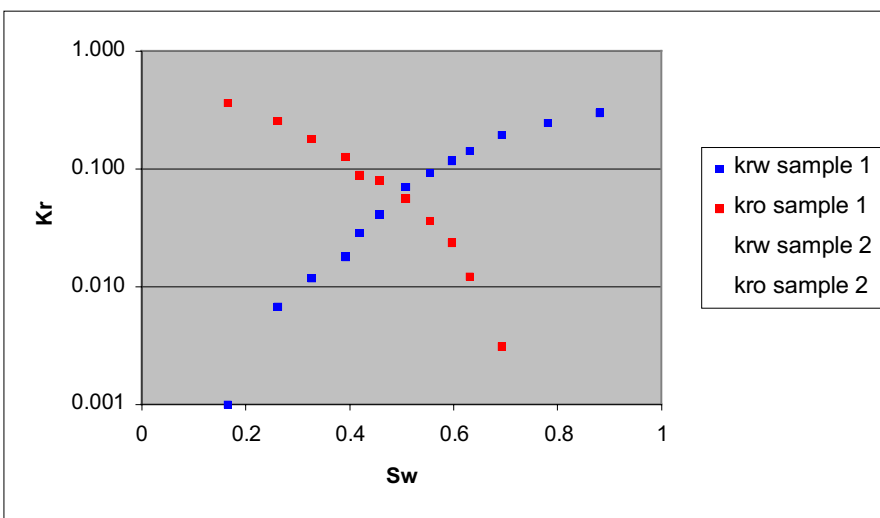


Figure 3b: Same as Fig. 3a, but now on a logarithmic scale

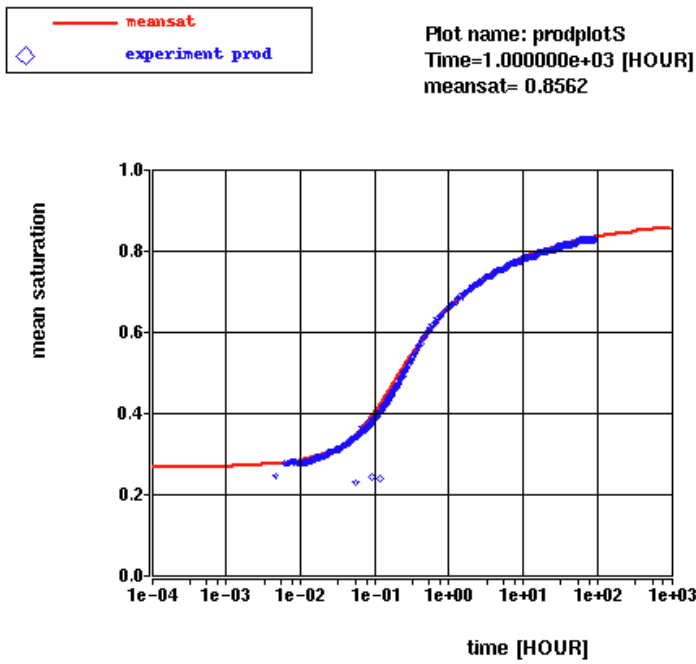


Figure 4: Numerical analysis of the centrifuge production curve. Dots are the measured data, the line is the best fit.

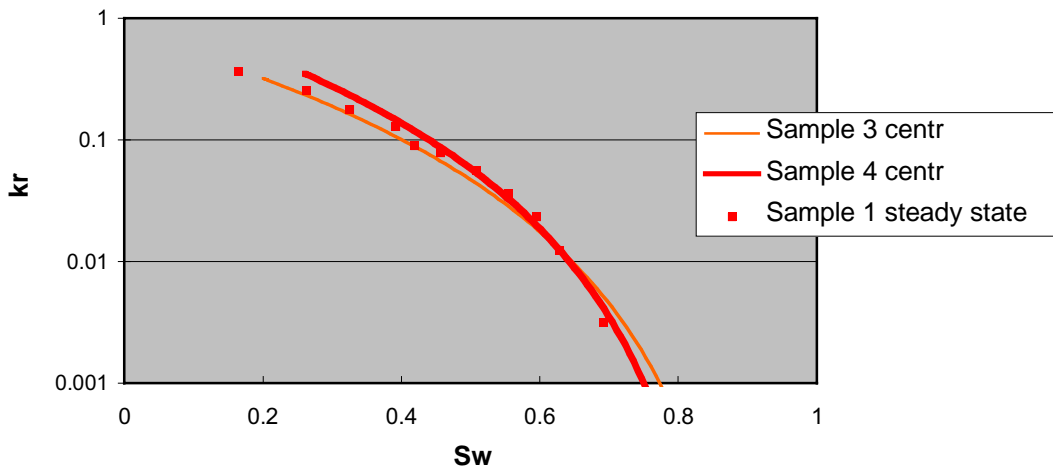


Figure 5: First imbibition relative permeabilities of crude (k_{ro}) as measured with the centrifuge on samples 3 and 4, and with the X-ray steady state on sample 1. Measurement fluid in the centrifuge is crude, in the steady state decane.

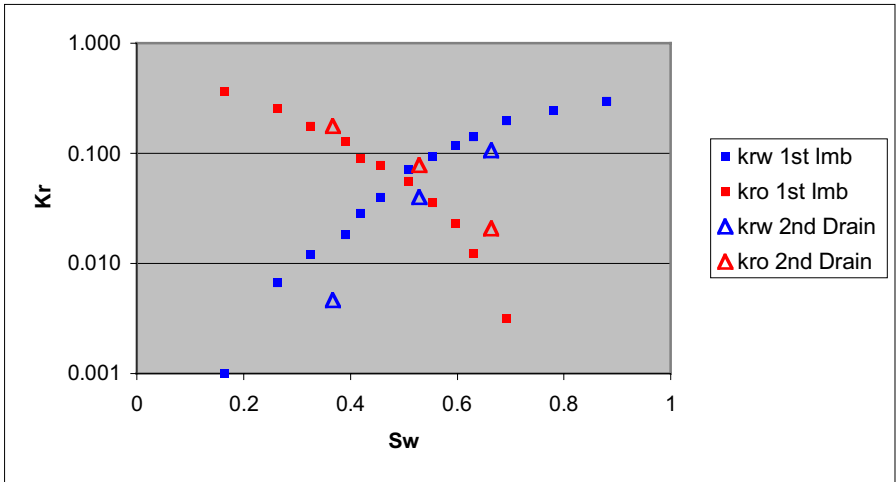


Figure 6: *hysteresis of relative permeability for oil and water; sample 1. First imbibition and secondary drainage.*

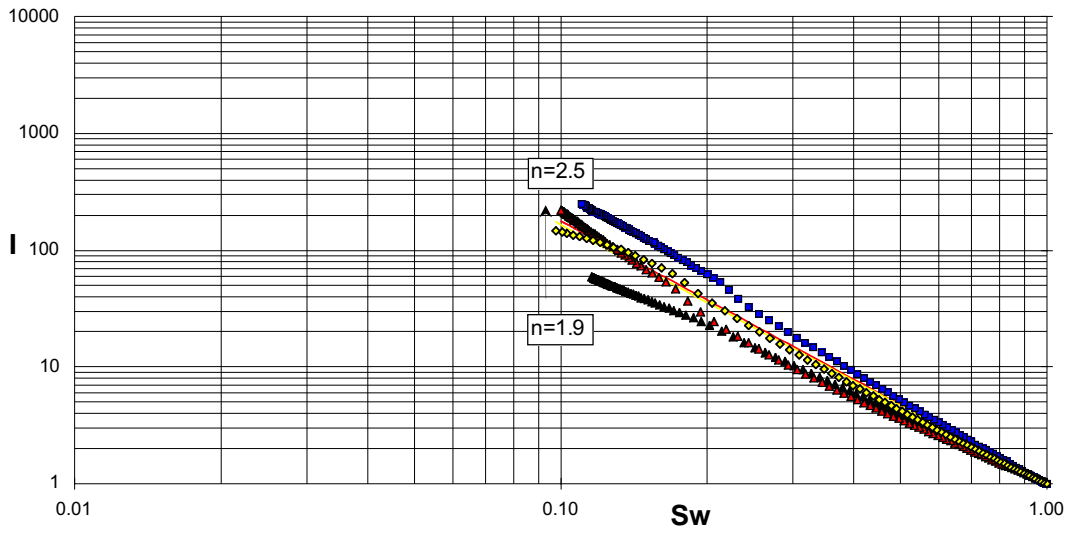


Figure 7: *Some resistivity (I-Sw) measurements from the continuous injection method. Used fluids are brine and kerosene. $n=2.2$.*

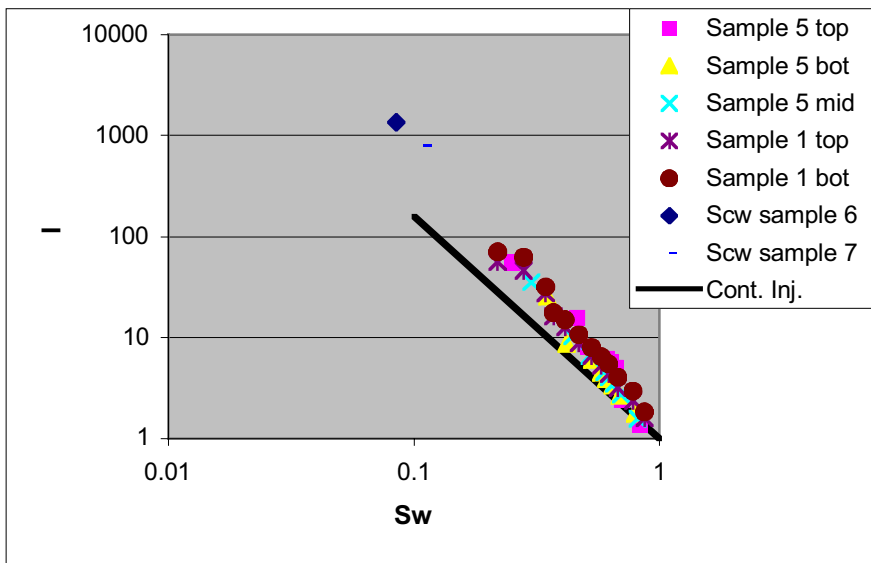


Figure 8: Some resistivity (I - S_w) measurements from the X-ray steady state. Different voltage probes can be read, resulting in resistivities measured over the top, middle or bottom of the core. For sample 6 and 7, separate resistivity values were measured over the top of the sample at connate water. Black line is the result of the continuous injection method on water-wet sample.

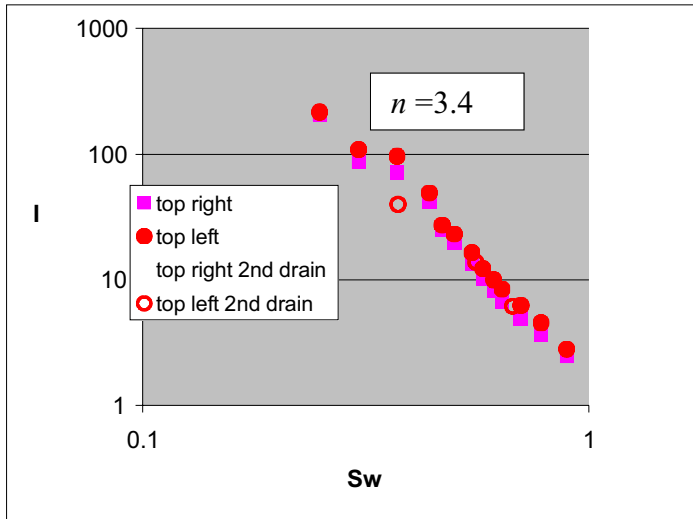


Figure 9: Hysteresis behavior of the I - S_w of sample 1.