A CASE OF LARGE HYSTERESIS ON RESISTIVITY INDEX VALUES BETWEEN DRAINAGE AND IMBIBITION PHASES

B.Lalanne, G.Hamon, S.Peltier, A.Saint-Pierre
TOTAL, CSTJF, Pau, France

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ABSTRACT

In paper SCA2009-01, we reported the case study of a high-permeability waterflooded reservoir, in which available single-well tracer test (SWTT) and Dean Stark data were consistent, both indicating a residual oil saturation (ROS) between 9 to 15 %. On the other hand, conflicting oil saturation values of around 50 % were calculated from Electrical logs (E-Logs), clearly much too high and inconsistent with the fact that the study wells had previously produced at very high water-cuts. Reasonable sensitivities on brine salinity, porosity and Archie cementation exponent "m" values (all calibrated from fluid samples and cores on nearby wells) did not significantly change the Sw values derived from E-Logs.

The Archie saturation exponent "n" was suspected to be the major uncertainty, considering the fact that the only available data for Resistivity Index RI measurements were old 1st drainage RI experiments, while the waterflooded reservoir was actually in imbibition. This logically triggered new RI measurements in both drainage and imbibition on cores from the well in question. The drainage "n" value proved to be around 1.8, consistent with old SCAL results, but imbibition "n" values exceeded 5, thus allowing the ultimate reconciliation of the SWTT, the Core Dean Stark, and the Electrical Logs' results of remaining oil saturation.

INTRODUCTION

In this paper, we report core RI measurements performed in both drainage and imbibition on a waterflooded reservoir, data that were acquired in an attempt to reconcile conventional E-Logs *calculated* oil saturation with Soil *measured* using other techniques (SWTT test, NMR Scanner Stations, Dean Stark core measurements).

NB: the convention in this paper is that *"drainage"* refers to oil displacing water (decreasing Sw), and *"imbibition"* to water displacing oil (increasing Sw), this regardless of the actual wettability.

RESERVOIR CHARACTERISTICS AND PRODUCTION HISTORY

The studied reservoir is described in paper SCA2009-01 by Batias & al.[8], in which field characteristics and production history have been detailed. The study focused on one of the field reservoirs deposited in a delta plain environment, whose main characteristics are: decametric Net Thickness, Darcy-like permeabilities, high porosity (~ 30 PU) and low clay content (< 7% in weight).

Reservoir history

Oil production from this reservoir started in 1977, by natural depletion. No water or gas injection was performed. The 1st water breakthrough occurred in 1980, and since 1990, the downdip wells have been produced at very high water-cuts. In the 1980's, this reservoir was selected for an EOR surfactant pilot, with a 5-spot well pattern drilled between September 1983 and January 1984, wells which quickly produced at very high water-cut, and then watered-out. The EOR pilot was not carried at that time, but this location was considered again in 2006 for a new chemical EOR pilot.

ESTIMATION OF REMAINING OIL SATURATION ROS

As detailed in paper SCA2009-01, a dedicated suite of operations was then designed in 2007 – 2008, so as to estimate the ROS on the 5-spot waterflooded area, for which the ROS campaign results are summarized on Figure 1:

- 1) Well production tests: they confirmed that the reservoir produced at very high water-cut > 99% (brine salinity 3.5 g/l), with the remaining oil being therefore very close to residual saturation conditions.
- 2) A single-well tracer test (SWTT), whose interpretation resulted in an Sor value of around 10% in the main flowing layer.
- 3) Dean Stark measurements of oil saturation from cores cut with WBM (low core invasion strategy plus "liquid trapper™" from Corpro) in new wells drilled in the watered-out zone, which yielded consistent Sor ~ 7 to 15 % as shown on track 3 of Figure 1 (green dots).
- 4) A suite of logs, including NMR Scanner stations which were run on 3 locations of the reservoir section in the new cored well, the NMR Soil (red squares on track 3 of Figure 1) being quite in line with the Sor values measured on core.

In summary, the 4 acquisitions were consistent in indicating oil very close to residual saturation conditions, with Sor values ranging from 7 to 15 % on average.

COMPARISON WITH CONVENTIONAL E-LOGS RESULTS

The only concern is calculated water and oil saturations from resistivity logs, as shown on Figure 2:

- While the calculated porosity is in line with the one measured on core (track 4),
- The 1st estimation of E-Logs derived oil saturations are around 50 % (track 5, Soil = 1 - Sw), i.e. drastically different from the SWTT / NMR / core Sor previously estimated at 7 – 15 %.

This 1st estimate of Sw calculation is derived from Archie exponents "m" = "drainage n" = 1.7 measured in the past on SCAL plugs, plus brine salinity set at 3 kppm. It must be emphasized that:

- Reasonable sensitivities on brine salinity / Rw and Archie "m" exponent did not result in any significant change of the calculated Sw.
- Sw calculation in downdip wells located in the original aquifer yielded Sw very close to 100%, thus confirming the pair [Archie m, salinity] was correct.
- Likewise, the calculated Soil were correct in the oil reservoir not yet waterflooded, i.e. E-Logs Sw calculated with drainage "n" = 1.7 were in line with the core-measured Sw derived from 1st drainage capillary pressure Pc.

Since the non-waterflooded sections Sw are correctly estimated, one can therefore suspect the problem is with the "drainage n" exponent, possibly not being valid in waterflooded sections where an "imbibition n" is more appropriate.

The sensitivity of Archie-derived Soil to "n exponent" is posted on Figure 3, from which one can conclude that "imbibition n" would have to be between 5 to 10 to expect a reduction from an Soil of 50 % Soil (calculated with n= 1.7) to one of around 10 - 20 % (as indicated by NMR, SWTT and Dean Stark). As such values are not commonly reported in the literature, this triggered new Core Resistivity Index RI measurements in 2009 – 2010, in both drainage and imbibition.

NEW MEASUREMENTS OF DRAINAGE AND IMBIBITION RI:

Apparatus, procedures and equipment

The measurements have been performed with the Pc – RI "porous plate" method, as equilibrium times can be easily attained with these darcy-like permeability reservoirs (in any case, each of the 3 successive phases, namely Forced Drainage, Spontaneous Imbibition & Forced Imbibition, lasted for at least 2.5 months).

The Porous Plate experiment, schematic summarized on Figure 4, has been performed on 3 plugs, mounted at reservoir temperature and effective stress (83°C and 120 bar), using native reservoir stock-tank oil, and 3.9 g/l aquifer brine. The bottom ceramic is "water-saturated" to allow 1st drainage of water, while the upper one is "oil saturated" to allow water displacing oil during Imbibition. Note that the cell is never dismounted between Drainage and Imbibition phases (use of by-pass valves). Prior to starting 1st drainage, the plugs have been cleaned so as to re-set the plug wettability to water-wet. At the end of the 1st drainage, the plugs remained ~ 2.5 months close to Swi, so that "aging" took place naturally during the process.

The Porous Plate RI experiments were completed by a waterflood phase after the Forced Imbibition (by-passing the ceramics, c.f. schematic on Figure 5), so as to make sure the plugs were indeed at residual Sor. Resistance was still monitored during the waterflood, but did not drift significantly from the one measured at the end of forced Imbibition. Waterfloods were performed at 10, then 5 and 1 cc/hr (5 Vp volumes injected each time), 1st downward then upward, without significant change in resistance or Sor.

One plug was dismounted at the end of the experiment to measure the resistance profile along the plug. As can be seen on Figure 6, the resistance profile is "regular", indicating the Sor distribution was most probably homogeneous within the plug.

Experimental results:

One of the 3 RI experiments ran without problem, with equilibrium times being attained as can be seen in Figure 7. The 3 first phases (F.D, S.I, F.I.) correspond to the Porous Plate experiment itself, as illustrated in Figure 4. The last phase, W.F., corresponds to the final waterflooding, as illustrated in Figure 5.

To detect possible drift on Ro (hence bias on RI = Rt / Ro), the composition of the brine was analyzed at the end of imbibition. As can be seen in Figure 8, the brine is slightly saltier than it was when starting drainage, meaning the resistance at end of imbibition is slightly underestimated. This explains the slight increase of resistance when starting the waterflood, on lower graph Figure 7, which results from the fact that new initial brine (slightly fresher) is injected in the plug. It is this last resistance value which is the most valid.

Final plots of RI – Sw are posted, from which Archie "n" exponent can be derived (Figure 9); in our case, we observe a strong hysteresis between "drainage n" ("n" < 2) and "imbibition n" (5 to 9), as speculated on Figure 3. Note, when entering the imbibition domain, the continuum of "n" values ranging from ~ 2 to ~ 9 for decreasing Sw values. As such, when dealing with waterflooded reservoirs, it may become quite difficult to conclude on which "n" values to use for the Electrical-logs interpretation, depending on whether the reservoir is at the initial (close to Swi) or at the final stage (close to Sor) of waterflooding. In such case, and particularly during a pre-screening phase for an EOR project, a combination of several independent techniques (SWTT, conventional E-logging, NMR logging, Core Dean Stark, RST or C/O logging, etc ...) may be needed to validate the actual remaining Soil.

The 2 other experiments didn't complete the Pc – IR Imbibition phase (ceramics problems during imbibition, while the plugs were already at 65 % Sw). However the drainage phases were fine and the plugs were then flooded from Sw ~ 65 % to Sor while monitoring the RI.

Finally, when superimposing the 3 plugs experiments (Figure 10), one can conclude that the "drainage n" is around 1.85, while the "imbibition n" ranges from 8 to 12. Error on measured Sw can have a strong impact on "n" at these low saturations, and Dean Stark measurements will be done to confirm the Sor. Yet, even considering a +/- 7 units of error on Sor, one can see on the table in Figure 11 that the "imbibition n" range would still be high, 5.4 to 14.2.

2nd pass of E-Logs calculation on waterflooded section:

Finally, the 1st pass of E-Logs computation (Figure 2) using preliminary but inappropriate "drainage n = 1.7" was re-assessed, using the core-measured "imbibition n" range (5.5 / 8 / 14). As can be seen in Figure 12, the fit is now quite satisfactory between SWTT test, NMR Stations and Core Dean Stark Sor vs the E-Logs derived Soil (c.f. the 3 scenario curves on track 4).

DISCUSSION

One-cycle Drainage – Imbibition "n" hysteresis is a well-known phenomenon in the industry, but the magnitude of the "n" hysteresis reported in this paper (1.87 in Drainage to 8 – 12 in Imbibition, even at low Sor ~ 15 %) looks particularly significant and on the high side of hysteresis values found in the literature. As developed here below, several papers report high "n" values, which either correspond to cases of:

- High "drainage n" values in strongly oil-wet reservoirs (but the "imbibition n" prior to this drainage is generally not reported).
- Or high" imbibition n" values but generally after an *extra* 2nd cycle of Drainage – Imbibition.

Papers reporting minor drainage – imbibition D – I "n" hysteresis

Several authors reported cases of only minor D – I hysteresis effects on "n" between drainage & imbibition ($\Delta n < 1$), cases which are not reviewed in the present paper.

Papers reporting high "drainage n" values in strongly oil-wet reservoirs

Many publications from the 50's to 80's focused on the effect of initial wettability and dealt with comparison between classic "drainage n" values on water-wet samples compared to high values "drainage n" on strongly oil-wet samples, such as in the pioneering works from Keller (1953)[1], Sweeney & Jennings (1960)[2], Morgan & Pirson (1964)[3], and later, Donaldson & Siddiqui (1989)[4].

They all reached similar conclusions that "drainage n" can be increased from low values (1.5 to 2.5) on water-wet samples to high values of "drainage n" on oil-wet samples (5.7 / 8 / 11.7 / 25.2), and that there is often a linearity between "n" and wettability.

The case study of Sweeney & Jennings (1960)[2] and Morgan & Pirson (1964)[3] are posted in Figures 13 and 14 respectively. They show that very high "n" values can be obtained on strongly oil-wet samples. The case of Morgan & Pirson (1964)[3] in Figure 14 is interesting, because it shows that very high "n" values can still be attained even at very high water saturation (n ~ 9.3 at Sw > 90 %), hence some similar conclusions compared to ours (Figure 10).

However, these 50's to 80's studies concern "drainage n" only, and the "1st imbibition n" waterflood curve located between the "1st drainage n" curve (water-wet case) and the "2nd drainage n" curve (when sample has turned to oil-wet) is missing as imbibition experiments were not carried out. Unlike our case in Figure 10, we cannot therefore strictly conclude on the magnitude of the hysteresis between the "1st drainage n" and the "1st imbibition n" in waterflood. Note as well the fact that the rock surfaces were generally treated with either silicone or naphtenic acid to achieve oil-wet conditions, and not during an "aging" process with native reservoir oil.

Papers reporting significant "n" hysteresis between drainage and imbibition

We can report 2 cases, Wei & Lile (1991)[5] study, and the one from Moss & Jing (1999)[7].

Wei & Lile (1991)[5] case study

Wei & Lile observed small to negligible hysteresis on water-wet samples (Figure 15 left, cycle 1 to 2a, with "n" remaining close to 2 in both drainage and imbibition), but significant hysteresis between imbibition and 2nd drainage, on oil-wet samples only (figure 15 left, cycle 2b to 3).

As we are analyzing D – I hysteresis, we have to look at the hysteresis between the 1st drainage curve (red circles curve labeled "1") and one of the imbibition curves (blue crosses labeled either "2a", or "2b", or "4" on Figure 15 left). It is clear on Figure 15 left that both combinations ["1", "2a"] and ["1", "2b"] yield only negligible to small D – I hysteresis on "n", and that the only pair yielding a strong hysteresis is the ["1", "4"] combination, as posted on Figure 15 right. Note that this last ["1", "4"] D – I case demands that an extra I – D phase (namely ["2b", "3"]) first took place, i.e. phase "4" is actually a 2nd imbibition phase, not a 1st imbibition phase (like curve "2b"). That could represent the case, for instance (other combinations possible), of an oil reservoir undergoing WBM filtrate invasion, then oil flushing back the water filtrate and finally a waterflood at a later phase.

This ["1", "4"] case on Figure 15 right presents some analogy with our Figure 10 case, but we must emphasize that our results were not obtained in *two D – I cycles* like the pair ["1", "4"], but in *one D – I cycle* only (like the pair ["1", "2b"]). In conclusion, our *one cycle* D – I "n" hysteresis (1.8 to 5 +) is therefore much stronger than the one reported by Wei & Lile (*one cycle* "n" hysteresis ["1", "2b"] = 1.9 to 2.9).

Moss & Jing (1999)[7] case study

This case (Figure 15) presents a lot of similarity with our results. In their study, Moss & Jing first measured a drainage – imbibition cycle on a preserved sample from an oil reservoir (preserved = not cleaned, and possibly in its original downhole wettability condition), then cleaned the plug to make it water-wet, and measured again a drainage – imbibition cycle. They used refined isopar oil for their imbibition experiment (compared to native stock-tank oil in our case).

They later proposed to mix the "cleaned" (water-wet) drainage case (red circles curve in Figure 16) with the "preserved" imbibition case (blue crosses curve in Figure 16) to mimic the behavior of a drainage on a water-wet reservoir, then imbibition (waterflood) on the preserved-wettability oil reservoir. They obtained the plot in Figure 16, which shows one of the strongest D – I "n" hysteresis reported in the literature, and which effectively presents some similarity with our Figure 10 case.

However, the "n" exponent of the preserved-state sample was measured *prior* to any core cleaning process, i.e. possibly still bearing the fingerprint of the drilling mud invasion process. Depending on the mud nature (OBM or WBM) and the reservoir state (at Sor or Swirr.), it may (or not) have induced an extra cycle of D – I.

CONCLUSION

1) In this paper, we documented a case of strong D – I "n" hysteresis between 1st drainage and 1st imbibition phases on a waterflooded reservoir, the hysteresis being apparently maintained up to high Sw / low Sor values. Some similar cases of high D – I "n" hysteresis have been previously reported in the literature. Strong hysteresis, however, often resulted from extra 2nd drainage – imbibition cycle.

2) Anyway, reconciliation between E-logs derived Soil and other Soil measurements derived from independent techniques (SWTT, NMR, Dean Stark) seems impossible on this study case if using «classic» "drainage n" values (i.e. ~ 1.8- 2.2).

3) More generally (and particularly when dealing with old cores measurements), appropriate "imbibition n" measurements are often not available. Then, in case of strong D - I "n" hysteresis, gross overestimation of Soil may result from E-logs interpretation on waterflooded reservoirs if inappropriate "drainage n" is used (and even in case of inappropriate "imbibition n" input, considering the possible large range of imbibition "n" values between initial (close to Swi) and final stages (close to Sor)). As such, within the scope of a pre-screening for any EOR project (or indeed any remedial work dependant on ROS estimation) on waterflooded reservoirs, the key to successful estimation of ROS relies on a combination of several independent techniques (SWTT, conventional E-logging, NMR logging, Core Dean Stark, RST or C/O logging, etc ...) to validate the remaining Soil.

ACKNOWLEDGEMENTS

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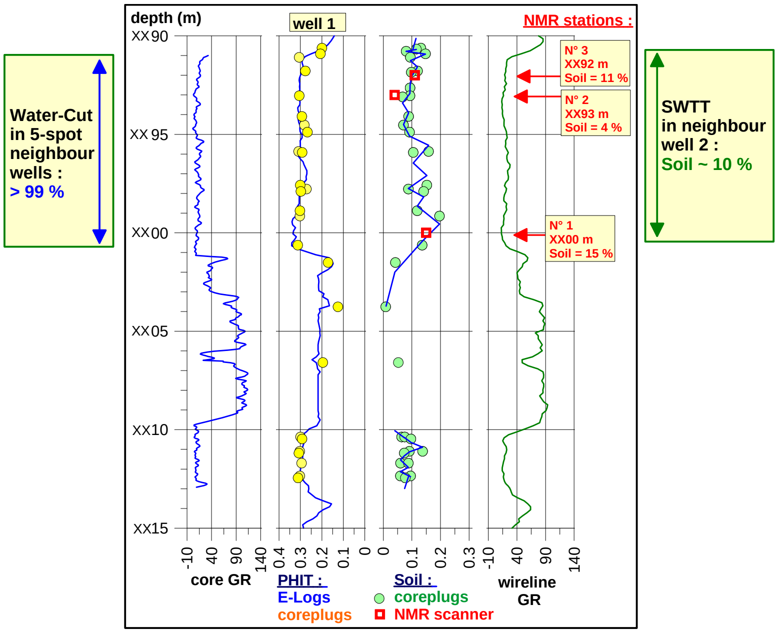


Figure 1: ROS campaign results

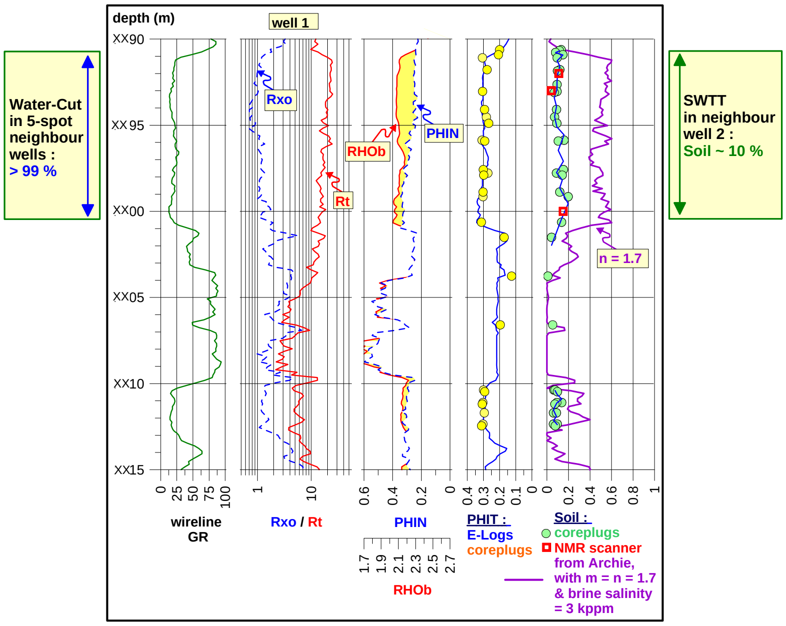


Figure 2: 1st pass E-Logs computation with n = 1.7

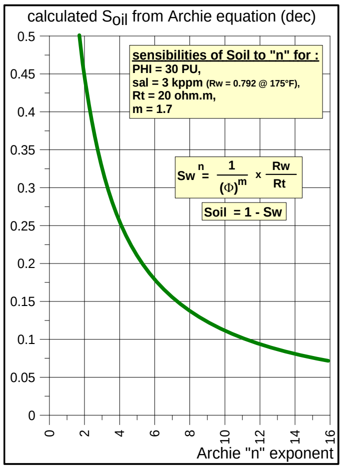


Figure 3: sensitivity Soil vs Archie "n"

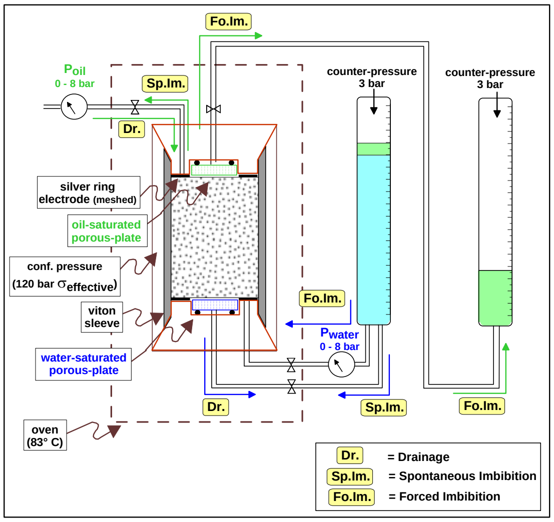


Figure 4: schematic of Porous Plate apparatus

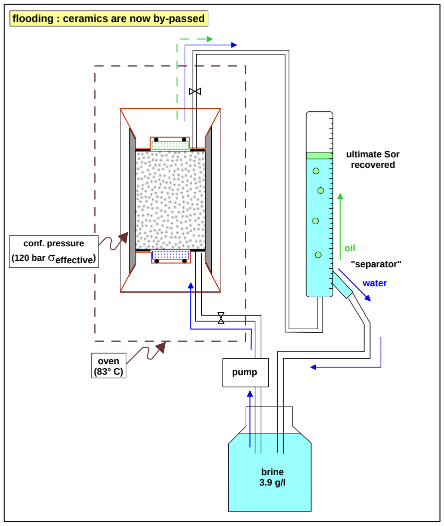


Figure 5: apparatus schematic for Waterflood phase

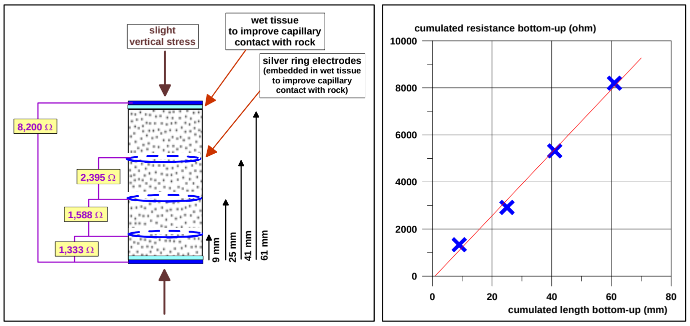


Figure 6: test for homogeneous distributions of the saturations

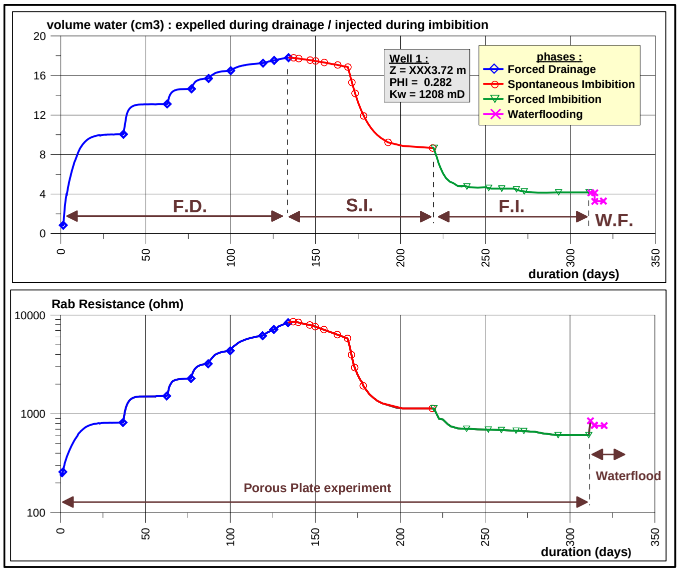


Figure 7: expelled water volumes and resistance

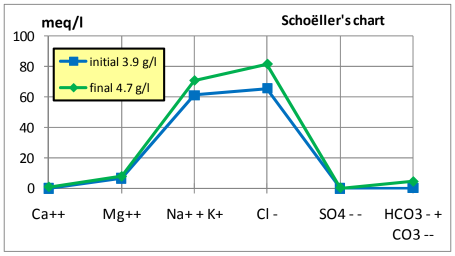


Figure 8: brine-in / brine-out composition

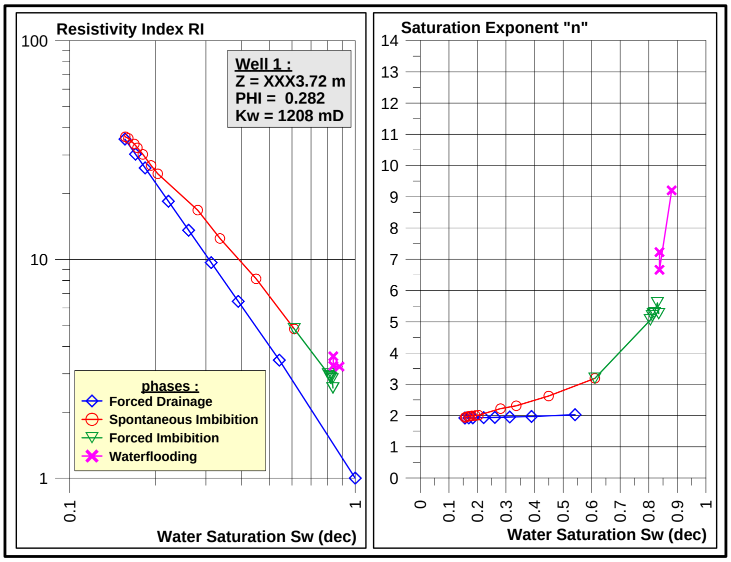


Figure 9: final plots of RI – n – Sw on the 1st plug

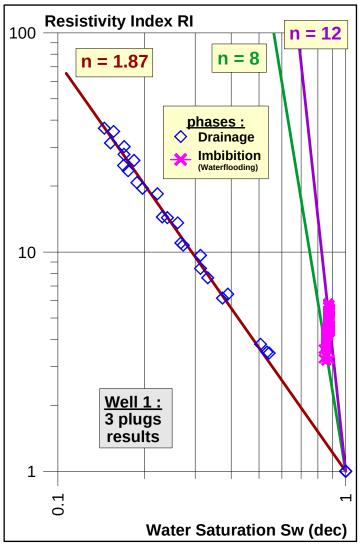


Figure 10: RI – Sw data for the 3 plugs

Sw	n
0.83	8
0.83 - 0.07	5.4
0.83 + 0.07	14.2

Figure 11: impact of a +/- 7 SU uncertainty on Sw on the "n" slope calculation

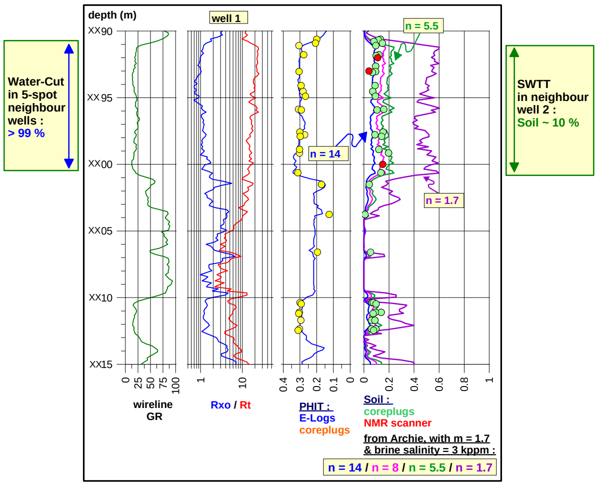


Figure 12: final pass of E-Logs computation

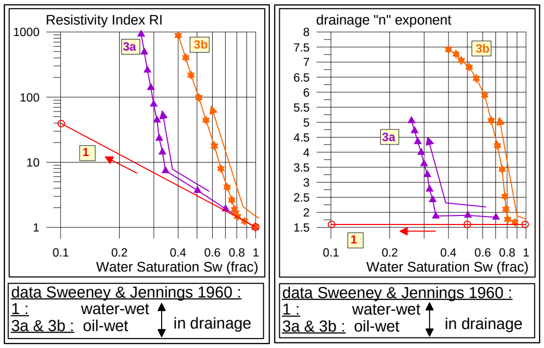
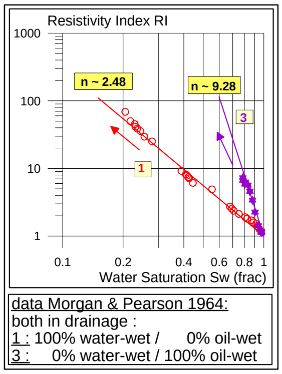


Figure 13: "drainage n", Sweeney & Jennings



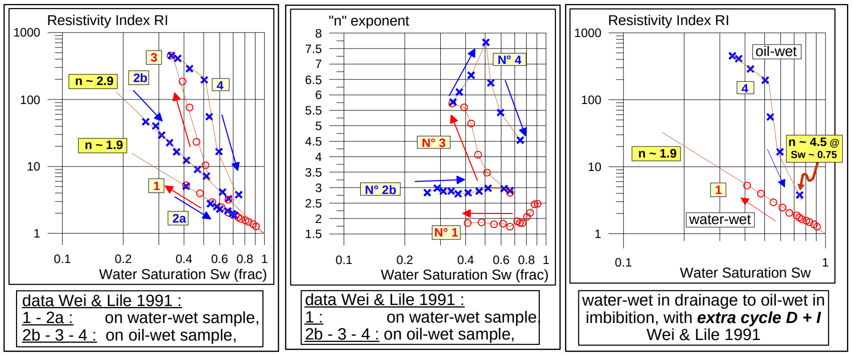


Figure 14:"drainage n", Morgan & Pearson

Figure 15: hysteresis between drainage and imbibition, Wei & Lile

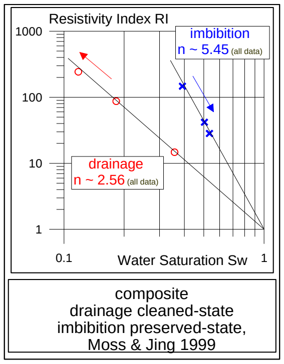


Figure 16: composite cycles, Moss & Jing
(Imbibition on preserved plug, Drainage on cleaned plug)