A fast method for trapped gas determination

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Abstract. Gas reservoirs are mainly produced by depletion with an aquifer rise; reservoir simulation requires two main SCAL inputs: the amount of trapped gas by the aquifer (residual gas saturation: Sgr) and the relative permeability to water due to aquifer flooding. As it is quasi impossible to predict aquifer strength, the primary SCAL input for reservoir simulation is the Sgr. The recovery factor is directly defined by initial and residual gas saturations. In fact, the residual gas saturation Sgr highly depends on the initial gas saturation Sgi and there is no universal petrophysical parameter governing the shape of this curve. This relationship can be described by several different models (Land, Aissaoui…). While Land's model is widely used, the Aissaoui model better fits the experimental results (Suzanne et al. 2003), at least for homogeneous sandstones. For a given threshold of initial gas saturation Sg0, this relationship typically exhibits a plateau at high Sgi>Sg0 and an increasing linear trend at low Sgi<Sg0. The challenge here is to properly estimate the value of the Sg0 threshold. Classical laboratory method would require one experiment per point in the Sgr/Sgi plot, and therefore can be achieved in a matter of months. Here we propose a laboratory method allowing the acquisition of the Sgr/Sgi curve in a few days. The proposed method combines centrifugation and capillary rise under imaging. First, the centrifuge allows creating a saturation profile along a sample; measured by NMR. Then, capillary rise is used to capture Sgr under NMR monitoring. By adding NMR imaging, this technique allows combining the benefits of centrifugation to explore a wide range of Sgi; and the ease and cost effectiveness of capillary rise to measure the resulting Sgr. Therefore, at a timescale close to a traditional capillary rise, the proposed technique avoids Land extrapolation and provides a direct measurement of Sgr in a wide range of Sgi. As an additional benefit, the combination of NMR and centrifuge can provide at the same time a direct measurement of capillary pressure, providing information on the gas in place and potential imbibition process in the reservoir.

1 Introduction

With stronger and stronger economic and environmental drives, gas reservoirs are becoming more attractive. At the discovery of a gas reservoir, it is essential to evaluate the amount of Gas In Place (GIP). This is commonly done by using the primary drainage capillary pressure curves. In some cases like a rise of the aquifer previous to the discovery, the reservoir can be undergoing an imbibition process at discovery. In this case, imbibition capillary pressure curves are required to describe the gas saturation between the original free water level and the current free water level. Then, production is mainly done by depletion with a rise of the aquifer. With the pressure drop and the subsequent encroachment of the aquifer into the gas reservoir, water traps gas. As gas fields are generally considered water wet, the three main inputs to reservoir simulation are: the amount of trapped gas by the aquifer (residual gas saturation: Sgr); the relative permeability to water (krw) due to aquifer flooding; and the relative permeability to gas (krg). Considering ultimate recovery from a water wet system, Cense et al. [[1]] recommend to focus on krw(Sgr) and Sgr. Indeed, krg has a large impact on pressure in reservoir models but its effects on ultimate recovery is low compared to Sgr and krw(Sgr). Furthermore, if the aquifer rise happened before the depletion (imbibition is the current process in the reservoir), the residual gas can expand during depletion and reconnect, therefore becoming an extra gas source ([[1]]). This paper focuses on the estimation of trapped gas saturation Sgr. Literature studies highlights that Sgr is linked to initial gas saturation, pores size, coordination number, ratio between pore throats and pores diameters and wettability. But usually Sgr is characterized as a function of initial gas saturation Sgi. This dependence of trapped gas saturation with initial gas saturation can be tackled in two ways:

1. Modeling this correlation.

Various authors provide empirical relationships to predict Sgr behavior: Land, Aissaoui, Jerauld...([[2],[4],[6],[16]]) All these studies bring out a strong link between Sgr and

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Sgi but none of them provide an exhaustive model available for all kind of rocks. Land's model is the mostly used to describe Sgr as a function of initial gas saturation (Sgi). It only requires one parameter which can be obtained with a capillary rise on a core plug at irreducible water saturation (Swirr). Assuming that Sgr obtained from a dry rock (SgrM) is really close from Sgr(Swirr), Suzanne et al.[[2]] , an easy and quick spontaneous imbibition with a foot bath (co-current imbibition) is sufficient to use Land's relationship. However, experimental results from Suzanne et al.[[3]]show a better fit with Aissaoui model. These observations on numerous sandstones confirm a bilinear model: for a given threshold of initial gas saturation Sg0, this relationship typically exhibits a plateau at high Sgi>Sg0 and an increasing linear trend at low Sgi<Sg0. Sg0 must be between 0.4 and 0.6 for sandstone. The challenge behind Aissaoui model is to capture parameter Sg0. Good description of Sgr/Sgi plot requires long time experiments that leads to sacrifying this model to Land's.

2. Measuring this correlation.

From laboratory side, trapping of gas by liquids is weakly dependent on fluid pressure, temperature and displacement rate, ([[1],[5],[6],[7]]). Trapped gas saturation can be measured experimentally using different techniques. It is one of the answers provided by core flooding experiments, but it can also be estimated from easier, faster and cheaper measurements such as capillary spontaneous imbibition. However, many experiments are required to populate the Sgr vs Sgi curve. The major limitation of this technique is its duration; which is often linked to permeability. Indeed, after a capillary trapping, a diffusion regime begins that appeared like an extra fluid absorption and translates into an underestimation of trapped gas. Moreover, co-current spontaneous imbibition could be subject to unpredictable artifact like counter-current flow of gas as described by Bona et al. [[8],[9],[10]].

Considering models review and parameters governing Sgr, there is a price to pay: a short time answer can only be obtained from the use of a model (such as Land), a real estimation of the Sgr/Sgi relationship requires long and tedious laboratory measurements. Two interesting experimental methods have been proposed by Maloney et al. [[11]] and Bona et al. ([[8],[9]]). The concept behind these techniques is to provide more points than the classical methods within the same purpose to describe Sgr vs. Sgi trend. Maloney's technique deals with a three phases measurement based on core flooding to provide enough data from a single test. Another interesting method has been proposed by Bona et al. ([[8],[9]]) where they combine centrifugation, NMR imaging and forced imbibition to provide a fast estimation of Sgr-Sgi. This method ensures a rapid and co-current imbibition, but it requires many steps in the centrifuge. Here we propose a method based on spontaneous capillary rise to provide Sgr description as a function of Sgi. It is fast, accurate and can provide the same results as many conventional capillary rise experiments in a matter of days. The method consists in generating an initial gas distribution along a core using a Pc field created by a centrifuge. Then, Sgi is obtained along the core by measuring water volume along the sample. Next, a foot bath is brought to sample and the evolution of the water front is monitored in an NMR imager. This combination of techniques allows simultaneous determination of primary drainage Pc curve ([[12],[13]]) and Sgr on a wide range of Sgi. One of the additional benefits from adding imaging on the co-current imbibition is to be able to capture abnormal behavior, as well as a counter current gas flow for example.

2 Outline of the Method

The proposed method starts with a sample fully saturated with brine and characterised by NMR profiling. Then, a Pc gradient is applied along the sample with a centrifuge. When equilibrium is reached, resulting volume profiles are acquired using NMR while respecting rotating direction. In order to avoid gravity re-equilibration of the saturation profile during the NMR acquisition, the part of the core containing the highest amount of brine (farthest face from rotor axis) is placed at the bottom of the NMR. Fully saturated and centrifuged profiles allow the calculation of water saturation as well as Sgi along the core. At this step, a capillary pressure curve can be obtained, following the method proposed by Green et al. ([[12],[13]]). Next, without handling sample from the NMR; a foot bath is brought to the bottom face of the core. The level of the foot bath is made constant, as presented in equipment section (Figure 1). Monitoring of the volume of imbibed fluid is performed by continuous measurement of the volume in the graduated cylinder and NMR. Periodic NMR profiling is also run to acquire water volume along the sample with a resolution of 1mm. Data processing is based on the same method used by Suzanne et al. [[2],[3]]: spontaneous imbibition of a wetting fluid can be described by Handy's law [[5]]; therefore for each slice of 1mm, gas saturation (1-Sw) is plotted against the square root of time during the process. Usually, two linear regimes are observed during imbibition:

- a first straight line capturing capillary dominated regime,
- a second straight line corresponding to a diffusion dominated regime.

When these two trends are captured by the method, the intersection of the two lines gives the trapped gas saturation. Obviously, this method clearly depends on the sample length to describe a wide range of Pc vs. Sw primary drainage and Sgr vs. Sgi. However, if the first centrifuge run does not cover a range of Sgi wide enough, another centrifuge step can be performed at higher rotating speed without compromising the results. In fact,

considering rocks as strongly wetting to water, there is no hysteresis in a strongly water wet system as long as the applied Pc is higher than first centrifuge step ([[14]]).
A potential pitfall behind this method is the redistribution of fluids in the sample during the NMR measurements. Particular care is taken to record NMR profile evolution with time. This allows the verification that no fluid redistribution happened.

3 Equipment and Procedure

3.1 Equipment

Saturation measurements: Volumes profiles were acquired using NMR profiling on a 2MHz Geospec from Oxford Instruments. The 1D SE-SPI (Spin Echo Single Point Imaging) saturation profiling was performed with a resolution of 1mm using Green Imaging Technology Systems software.
Capillary rise: The core plug is placed in NMR using an in-house Teflon cell. This cell is adaptable to core length to limit evaporation by reducing the air volume surrounding the plug, and equipped with a microscopic venting to avoid a pressure rise during imbibition. The cell position can be mechanically locked in position to ensure a perfect overlap of the different NMR profiles acquired (at 100% water, after the centrifuge and during capillary rise).
As shown in Figure 1, in order to maintain the foot bath level, a water reservoir is installed outside the NMR. This reservoir is connected to a burette to monitor the volume of imbibed fluid.

3.2 Procedure

As mentioned earlier in this paper, trapping of gas by a wetting fluid is weakly dependent on temperature and pressure. Therefore, all measurements were performed at ambient conditions using couple of fluid air and brine.
Sample characterization:
1) Clean with sequences of toluene and iso-propanol; dry by nitrogen flushing then heating at 80°C.
2) Measure permeability and Helium porosity.
3) Saturate with synthetic brine (Sw=100%) to determine pore volume.
Fully saturated properties:
4) Measure NMR profile @ Sw=100%.
Determination of first drainage Pc curves:
5) Spin the core in the centrifuge in drainage mode until equilibrium is reached.
6) Obtain the NMR profile.
Determination of Sgr curve as function of Sgi :
7) Perform a capillary rise experiment putting the core in a foot bath (1-3mm) monitored with a burette and NMR profiling.
8) If a larger range of primary drainage Pc vs. Sw or Sgr vs. Sgi is required: loop to step 5 and increase centrifuge speed.

4 Validation on outcrop Sample

The zone of interest behind the technique is low to medium permeability. In order to test the technique, a Richemont carbonate outcrop was selected. Basic petrophysical properties of this homogeneous carbonate, no apparent vugs, are presented in Table 1.

Table 1. Basic petrophysical properties of the presented Richemont core plug.

Property	Richemont sample
Porosity / p.u.	23
Permeability / mD	4.5
Diameter / mm	38
Length / mm	50

Following saturation, the sample was centrifuged in drainage mode at 1700rpm. Resulting Sw profile was acquired by NMR to populate Pc curve and obtain a first Sgi dataset. In order to cover a wide range of Pc and Sgr, centrifuge was relaunched (at 3000 and 3500rpm) after each capillary rise. Figure 2 presents the results of the technique on the Richemont outcrop sample: NMR profiles after each centrifuge steps are presented at the top, followed by resulting primary drainage Pc curve compared to classical porous plate (red crosses). From the NMR profiles, the sample can be considered as homogenous. Indeed, there is no substantial bumps and valleys observed along the sample neither for fully saturated profile nor after each centrifuge steps. The capillary pressure curve was computed according to the method proposed by Green et al. ([[12],[13]]). The sample was then submitted four times to the porous plate technique; but only three measurements are presented. Indeed, during a measurement pressure gauge acquired a wrong pressure. Thus, this point was discarded from the Pc results but was still right as starting point to apply a capillary rise. The superposition in the Pc curve of the points coming from the different centrifuge runs is an indication of the good quality of the experiment and indicates the good homogeneity of the sample. Moreover, points coming from porous plate technique clearly validate the good quality of Pc curve captured.

The Richemont outcrop sample was then submitted to a spontaneous imbibition in the dedicated setup and the capillary rise was monitored by NMR. In Figure 3 we present the NMR volume profiles acquired during the capillary rise experiment after centrifuging the sample at 3000rpm and the resulting gas saturation profiles. The water front observed in the NMR profile appears rather smooth and no sharp front or quasi-piston like displacement is observed. The entire time lapse experiment can be represented in a 3D plot where the NMR gas saturation profiles are represented versus time (right of Figure 3). Each 1mm thick slice undergoes a capillary rise experiment where the capillary regime from the diffusion regime can be separated. The value of trapped gas saturation Sgr can then be extracted. At the end, each slice has a given Sgr and an initial Sgi. Figure 4 presents all the Sgr/Sgi points obtained on the Richemont outcrop sample, prepared at three different centrifuge speeds (1700, 3000 and 3500rpm) and Sgr obtained after porous plate steps. Sgr as a function of Sgi could be described by two linear trends with a threshold at Sgi~0.4. After each porous plates measurement the sample was submitted to a co-current imbibition monitored by a balance. A good match is observed using classical method and proposed technique; therefore leading the validation of the proposed method

5 Results on Reservoir Samples

Two samples from a gas field were chosen to test the proposed method. Basic petrophysical properties of these heterogeneous carbonates are presented in Table 2.

Table 2. Basic petrophysical properties of the two reservoir samples A and B.

Property	Sample A	Sample B
Porosity / p.u.	14	12
Permeability / mD	0.4	0.4
Diameter / mm	38	38
Length / mm	45	43

Figure 5 presents the results of the technique on the two reservoir samples: NMR profiles at Sw=1 and after centrifugation at 4800rpm are presented at the top, followed by resulting water and gas saturation profiles after centrifugation. Then, the primary drainage capillary pressure Pc curve is presented. Finally, at the bottom are presented the resulting Sgr-Sgi curves. From the NMR profiles, sample A can be considered as homogenous while sample B appears more heterogeneous and exhibits a bump in the middle of the profile. However, this heterogeneity is not clearly seen on the profile after centrifugation. The capillary pressure curves were compared with mercury injection (MICP) obtained on the end trims of the plugs. While a good match is observed for sample A, there is a mismatch for the transition zone for sample B. This could be explained by the different techniques used (MICP versus centrifuge) and the fact that MICP measurements were done on end trims and not on the exact same sample. However, the raw estimations of Swirr from the two techniques are consistent. The two reservoir samples were then submitted to a spontaneous imbibition in the dedicated setup and the capillary rise was monitored by NMR. The entire dataset of NMR profiles monitoring the capillary rise experiment leads to the estimation of a trapped gas saturation Sgr for each 1mm thick slice. The final result of this experiment is the Sgr-Sgi curve presented at the bottom of Figure 5. In one single centrifuge step, a significant part of the Sgr-Sgi curve has been acquired. The obtained curve is coherent with classical capillary rise experiments (Red crosses on Figure 5). The classical points are obtained starting either from a dry plug or from a plug at Swirr. In this case, Swirr was set using a centrifuge, flipping the plug in order to limit the saturation profile. The two samples exhibit a bilinear behavior of the Sgr-Sgi curve. While for sample B Sg0 (threshold value between the two linear regions as defined by Aissaoui ([2, 3, 16]) is around 0.6, the Sg0 value for sample A is quite higher than expected (around 0.7). In both cases the Land model does not represent the reality of the complexity for these heterogeneous carbonates. In fact, the land model underestimates the residual gas saturations and is therefore quite optimistic in terms of reserves estimation. As mentioned above, the present method allows the simultaneous acquisition of primary drainage Pc curve and Sgr vs. Sgi curve. Therefore, results can be presented as a function of HAFWL (Height Above Free Water Level). Thus, Figure 6 presents for each reservoir rock the resulting water saturation from drainage (corresponding to Sgi) and imbibition (corresponding to Sgr) applied on the samples as a function of HAFWL. Final Sw are presented using both experimental points and Land correlation. A good way of comparing the impact of different Sgr-Sgi curves on the reserves estimation is to measure the area between the first drainage curve and the Sgr-Sgi relationship in Figure 6. Therefore, this results representation highlights the resulting recoverable gas overestimation using predictive Land relationship.

6 Discussion

The method proposed here is based on spontaneous capillary imbibition. This technique has been reported to be subjected to counter current imbibition when performed on plugs uniformly saturated ([[8]]), and therefore discarded by some authors. In this case, the operating procedures are preventing counter current imbibition to happen. The sample is prepared by establishing a non-uniform Sw profile. By doing spontaneous imbibition from the bottom of the plug (the part with the lowest Sgi), relative permeabilities are helping the gas to go toward the top (toward higher gas saturation i.e. higher gas relative permeabilities). Moreover, at high initial water saturation, the imbibition process is faster, increasing chances of having direct snap-off mechanism (as reported by Bona et al [[8]]), therefore preventing any counter current imbibition from happening in the rock slices located above. The proposed technique allowed the simultaneous acquisition of Pc vs. Sw primary drainage curves and entire Sgr vs. Sgi dataset for reservoir samples in a couple of days, therefore corresponding to operational timeframe. The experimental results appear different from the Land model therefore justifying the need for experimental data. Actually, the Aissaoui's bilinear model provides a better description of the experimental data than the Land correlation for the samples tested. The experimental data exhibits two linear trends which is better described by the Aissaoui correlation than by Land's. However, Aissaoui's model is not predictive because it requires the knowledge of the threshold point between the two linear zones (Sg0). While results on reservoirs rocks covered a satisfying zone on Pc and Sgr curves, a largest range of Sw and Sgi would be covered with a slower centrifuge speed than the 4800rpm applied on the two reservoir rocks. Actually, most of the Sgi points are really close. Thus, results with a lower centrifuge step could provide quasi-similar results with larger range of Sgi and Sw measured. Thanks to the combination of NMR, centrifuge and capillary rise Sgi and Sgr dataset can be represented as a function of HAFWL. This way it can easily be translated into reserves estimation for one given rock type. Thus, the final trapped gas can be plotted at the height coming from its Sgi. Observing results from the two reservoir samples, a transition zone of about a hundred meters was covered and leads to a non-negligible overestimation of recoverable gas using Land model. In this case, using predictive correlation causes errors of about 10% and 4% for samples A and B on the recovery. To summarize, the wider and higher the Sgr plateau, the larger the errors created using Land's relationship. Obviously, the impact of the Sgr-Sgi curves is concentrated on the reservoir zones that are not at Swirr. The real impact on the recoverable gas needs is then stronger for reservoirs with thick transition zones or exhibiting a paleo free water level.

7 Conclusion

Following a discovery, the two main SCAL objectives are to provide input for GIP estimation and ultimate gas recovery. Indeed, reservoir evaluation requires the primary drainage curve to evaluate the amount of GIP and residual gas saturation to capture the amount of gas left behind the aquifer front during production. As an aquifer strength is quasi unpredictable, the only way to reduce uncertainties on reservoir models is a good grip on Sgr. The best way to measure several Sgr within operational timeframe without using a predictive model is the classical co-current spontaneous imbibition. The idea behind a capillary rise is to reproduce what happens in the reservoir during the aquifer encroachment. However, as mentioned by Bona et al [[8]] classical capillary rise experiment could be subjected to a counter-current imbibition and lead to an overestimation of Sgr. By establishing a saturation profile in the centrifuge and measuring it by NMR, we not only obtain the primary capillary pressure curve, but also establish a starting point saturation for the capillary rise that will allow to cover numerous Sgi values in one single experiment. The kinetics of the capillary rise experiments is then followed by NMR, allowing the determination of Sgr for every single Sgi. The present method avoids the use of several drying of samples and facilitates measurement using brine as imbibed fluid and provides results in couple of days. Thanks to the use of imaging, the proposed technique opens possibilities of measuring Sgr even for tight rocks when the dynamics of the capillary rise is really slow and for which core flooding experiments would be extremely long and complex. Moreover, an additional benefit comes from beginning the capillary rise with a saturation profile. Indeed, a foot bath is applied on the sample face that contain highest amount of water; considerably reducing potential counter-current process. Furthermore, knowing that water is strongly wetting in presence of gas, no hysteresis happens between krw drainage and imbibition ([[17]]). Therefore, centrifuge could not only be used to establish the primary drainage curve but also to estimate simultaneously krw at least for the endpoint. Periodic NMR profiling on sample (seconds to minutes timescale per profile) ensures a good capture of the water front shape. K. Li et al [[15]] proposed a method based on capillary rise to estimate effective water permeability behind a sharp water front. Thus, capillary rise under NMR profiling provides enough information to use or discard Li's method. From results presented above, utilization of this technique cannot be applied, probably due to the low permeability purpose tested. However, NMR periodic profiling opens the door to deeper investigate this method. Discussion about the impact of the method were focused on GIP and reservoir production with an aquifer encroachment. However, the method could be obviously applied on secondary drainage and imbibition processes if required. Furthermore it could be used to study production scheme with reversal of direction of saturation change, such as gas storage in aquifers, WAG (Water Alternating Gas) or CCS (Carbon Capture and Storage).

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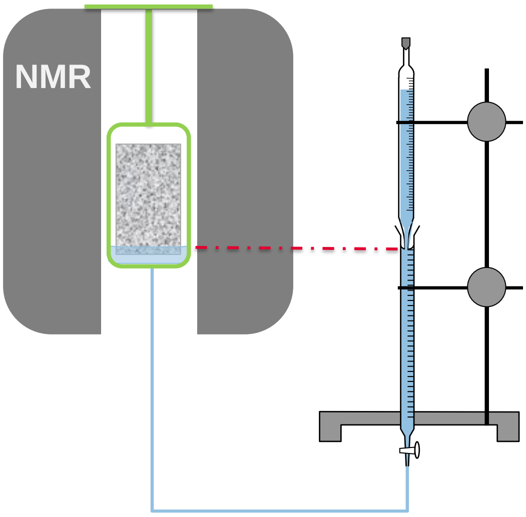

Figure 1. Capillary rise under NMR set-up.

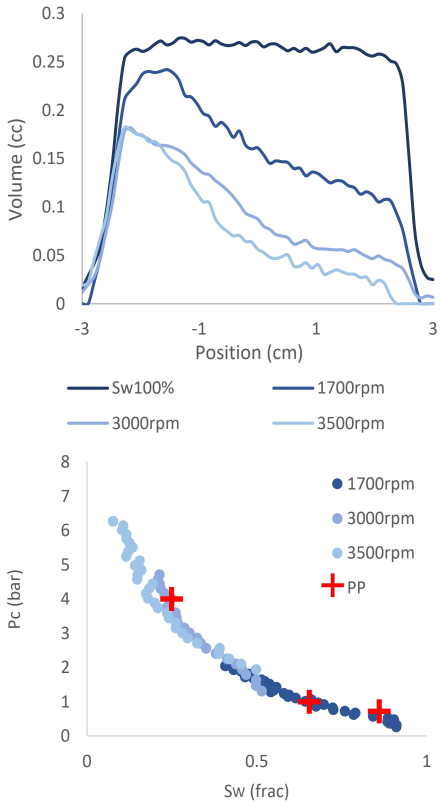

Figure 2. Results for primary drainage applied on the Richemont sample. NMR profiles (top), resulting Pc curve (bottom).

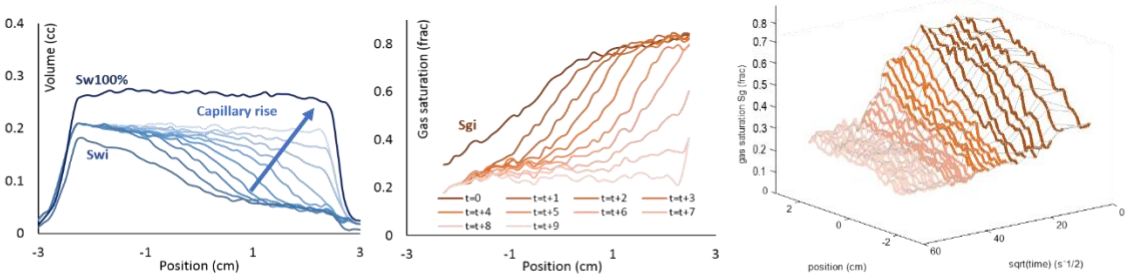

Figure 3. Capillary rise on Richemont, example prepared at 3000 rpm.

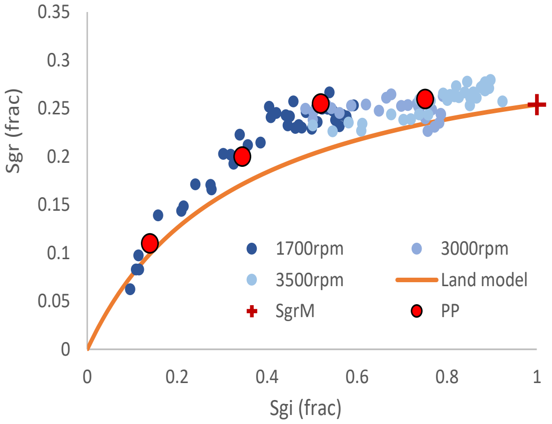

Figure 4. Sgr-Sgi results for the Richemont sample.

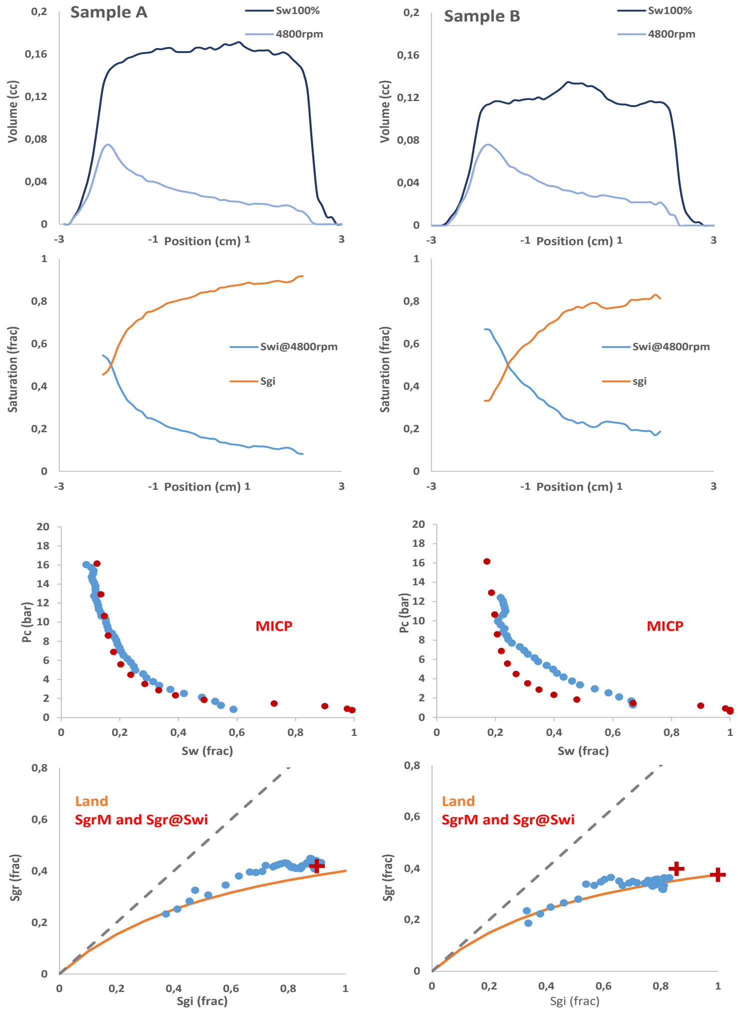

Figure 5. Results for primary drainage and capillary rise applied on the reservoir samples. From top to bottom: NMR profiles, resulting saturation profiles, Pc curves and Sgr vs. Sgi curves.

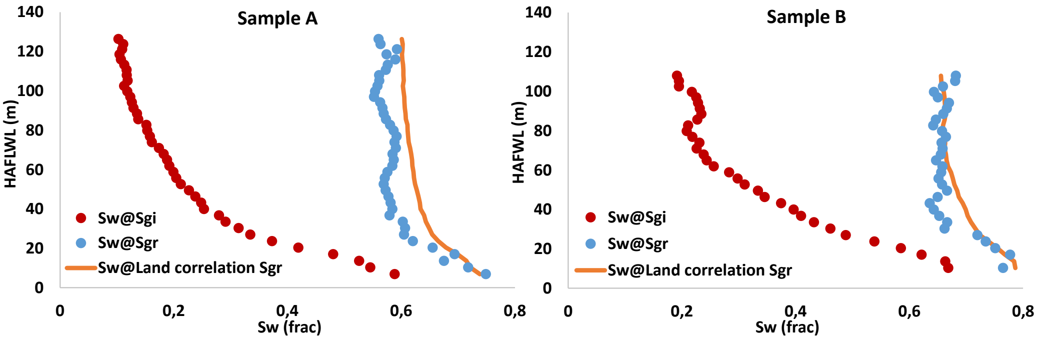

Figure 6. Results on reservoirs core plug represented as a function of height above free water level.