# SCA2003-36: IMPACT OF SCAL ON CARBONATE RESERVOIRS: HOW CAPILLARY FORCES CAN AFFECT FIELD PERFORMANCE PREDICTIONS

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## 1. ABSTRACT

Accurate capillary pressure data in both drainage and imbibition cycles can be essential for understanding hydrocarbon reservoir performance. Drainage capillary pressure is usually used to initialize reservoir static models, i.e., to determine initial saturation as a function of height above free water level and to calculate hydrocarbon volumes in place. However, imbibition capillary pressure is often not used correctly to model fluid flow in displacement studies. This is often due to a general lack of reliable experimental data to cover the predominant rock types during reservoir studies or the perception that effect of capillary force might become insignificant once production commences. In this paper we examine the effect of capillary forces in addition to viscous and gravity forces on sweep efficiency of immiscible displacement in a heterogeneous porous medium at different wetting conditions.

Capillary pressure curves have been measured using core materials from a heterogeneous Cretaceous carbonate reservoir in the Middle East. The core plugs were selected from different rock classes to cover a range of permeability from 0.1 to 1000 mD. Capillary pressure data were obtained in primary drainage and imbibition after aging the plugs at connate water saturation to restore wettability.

The results show, for the case under study, that there is a subtle balance between viscous, gravity and capillary forces during oil displacement. Ignoring any of these forces especially for non-water-wet heterogeneous reservoirs could lead to erroneous prediction and sub-optimal field development planning. The study shows that for the subject carbonate reservoir water-flood recovery is strongly dependent on the shape of the imbibition capillary pressure curves.

## 2. INTRODUCTION

In this paper we study the impact of capillary forces on sweep efficiency in heterogeneous carbonate reservoirs. The study was initiated in order to understand and explain the field performance of a major carbonate reservoir in the Middle East, which is currently under water flooding. The study is extended to discuss heterogeneous/layered carbonate reservoirs in general and the impact of the different

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forces that affect fluid flow. A brief description of the reservoir understudy is given below.

Fluid flow in porous media is governed by the interaction of viscous, gravity and capillary forces. It is well recognized that cross-flow has significant impact on sweep efficiency of immiscible displacement in layered reservoirs [1-10]. Both gravity and viscous forces have been extensively studied in the literature. However, the impact of capillary forces is generally under-estimated in field simulation studies. This is mainly due to a general lack of reliable experimental data to cover the predominant rock types during reservoir studies and the perception that effect of capillary force might become insignificant once production commences.

There are reported studies available in the literature on the impact of capillary forces on sweep efficiency in stratified reservoirs. However, most of the studies focused on water-wet systems. Mixed or oil-wet systems have rarely been studied. For example, it is often found that the drainage Pc curve was used to model water displacement studies [8]. As it is well established, water-wet reservoirs are exceptional and most reservoirs are of mixed-wet nature. Therefore, to apply conclusions based on water-wet systems to most reservoirs might be misleading and could result in poor reservoir management. In this paper we study the importance of capillary forces on field performance for a heterogeneous carbonate reservoir under different wetting conditions. Several combinations of viscous, gravity and capillary forces are studied. The impact of geological layering and cyclic permeability contrast on sweep efficiency and recovery has also been investigated.

## 3. RESERVOIR DESCRIBTION

The reservoir understudy can be regarded as a layer cake type reservoir where strata measuring a few feet can be correlated field wide, often over tens of kilometres. The overall permeability increases towards the top of the reservoir. A high level description indicates a reservoir that consists of two main bodies, i.e. an Upper zone (high permeable layers inter-bedded in between low permeable layers) and a Lower zone of low permeability layers. In the rest of the paper these two zones will be referred to as the Upper and Lower zones. The average permeability of the Upper zone is some 10-100 times higher than that of the Lower zone.

The prime recovery mechanism currently applied is water flooding. As reported in some literature studies permeability increasing upwards maybe very beneficial in a water flooding situation [1]. This conclusion is based on either neglecting capillary forces or assuming that the reservoir is water-wet such that capillary forces act to enhance water cross-flow and sweeps the low permeability layers. In the subject reservoir, field data shows that injected water tends to travel quickly through the Upper zone along the high permeability layers. This led to attempts to force flow through the Lower zone by completing wells separately in the Upper and Lower zones. However, because the dense zone boundary between the Upper and Lower zones proved not to be a barrier to fluid flow, even when both injectors and producers are completed in the Lower zone, water quickly crosses through the boundary to the Upper zone, and oil in the Lower zone tends to be by-passed. Flow of water from the

Upper to Lower zone occurs only in the vicinity of the producers due to pressure draw down. The traditional explanation for this water hold-up phenomenon is reduced vertical permeability at the interface between the Upper and Lower zones. However, field observations do not support this explanation as MDT and RFT data show that pressure communication exists between the Upper and Lower zones. Therefore, we need to seek another explanation for the water hold-up mechanism. Currently, the most widely accepted explanation for this phenomenon is a form of capillary pressure barrier [6]. By using the notion that different levels of (negative) capillary pressures apply to the Upper and the Lower zones, this field performance can be matched in simulation models. In this paper, this phenomenon is studied in more detail supported by laboratory SCAL measurements and field observations.

## 4. SIMULATION MODEL

The simulation work was performed using two different element models, a 3D model of 27 layers (50X7X27) and a 2D model of 160 layers (7X160). The vertical resolution of the second model is one foot. The thickness of the layers of the first model varies between 2 to 11 feet and the grid size in the x and y directions are 100mX100 m. More refined models were used by decreasing the x and y dimensions to 50 m but did not affect simulation results. Porosity and permeability within each layer is constant. Permeability and porosity as a function of depth for both models are shown in Figure 1. Also shown in the figure is the permeability of the samples used in the SCAL study discussed in section 6.1. In all the simulations carried out in this work, a vertical injector was placed in one corner of the model and a vertical producer was placed in the diagonally opposite corner. Initial fluid distributions were assigned to the model using drainage capillary pressure curves and then imbibition capillary pressure is used as water flood starts.

## 5. RESULTS

### 5.1 Impact of Water-wet, Zero and Oil-wet Capillary Pressure

To investigate the effect of capillary forces on oil recoveries and sweep efficiency, three simulated water/oil displacements were performed using positive, zero and negative imbibition Pc curves (cases 5, 3 and 7 discussed next section). In the three runs all parameters in the model are assumed identical and the same drainage Pc curves are used to initialize the model. Oil and water production, as a function of injected water volume, are shown in Figure 2. Figure 3 shows an x-z cross section of the three runs. Positive Pc results in a very good sweep in both Upper and Lower zones, the flood front moves almost homogeneously and low and high permeable layers are swept simultaneously. In the case of zero Pc the front moves faster in the Upper zone but there is still very good sweep in the Lower zone. This is not the case when a negative Pc is used. Most of the injected water moves to the Upper zone and it stays there. While the Upper zone is almost completely swept, there is very little sweep of the Lower low permeable zone. Comparing the oil production from the three cases shows that up to water breakthrough the total recovery is the same, however, the oil is produced from different parts of the reservoir. This demonstrates that if only total production is taken into account, (e.g. during history matching) misleading conclusions may be drawn. Ignoring capillary forces, or not taking them into account from day one, may not give the correct picture of where the remaining fluids are and, consequently, could lead to non-optimal development planning decisions.

It is important to understand the sweep efficiency shown in Figure 3. The models are initialized using primary drainage capillary pressure curves, as drainage is the process which takes place during the charging of the reservoir. In static conditions the capillary pressure at the interface between a high and low permeable layers is the same, i.e., water pressure and oil pressure at the interface is the same. As the flood starts and when the viscous forces are dominant (i.e., near the injector), the water front advances faster in the high permeable layers (proportional to the K*H values of each layer). Viscous cross flow will also cause the water injected in the low permeable layers to travel to the high permeable layers. As a result a region develops where water in the high permeable layers is in contact with low permeable layers saturated with oil. The difference in capillary pressure between the high and low permeable layers causes differences in the water and oil phase pressures, and forces water to cross flow from the high to the low permeable layer and oil to flow in the reverse direction. This results in the front in the high permeable layer being retarded and the front in the low permeable layer being advanced relative to their position in the absence of cross flow. This cross flow occurs until vertical equilibrium is established. The above is true for all cases regardless whether the reservoir is water-wet or oil-wet. For water-wet conditions the low permeable layer has a higher positive capillary pressure and for capillary equilibrium to be established the water saturation in the low permeable layer needs to be higher than that in the high permeable layer. However, for oil-wet conditions where the low permeable layer has more negative Pc, capillary equilibrium is established at very low water saturation in the low permeable layer and appreciable cross flow only occurs as the saturation in the high permeable layers approaches residual oil saturation.

In the reservoir understudy where the high permeable zone is at the top, the gravity forces and water wet capillary forces align (i.e. act in the same direction, helping to flood the Lower reservoir) and result in very good sweep efficiency, as shown in Figure 3a. For zero imbibition Pc, only gravity will act to move water downward but this still results in a good sweep of the Lower zone (Figure 3b). However, for non-water-wet layered reservoirs capillary forces will act opposite to gravity and that may result in a barrier which prevents water from moving downwards. This will lead to poor sweep of the Lower zone as shown in Figure 3c. An oil-wet low permeable layer with negative capillary pressure is not sufficient in itself, to prevent water that first entered the high permeable upper layer from spreading into bottom low permeable layer. For the capillary pressure to counter-act gravity forces and work as an effective barrier, the capillary pressure difference between the low and high permeable zone has to exceed the gravity force which results from the water column in the high permeable zone. For a very thick reservoir and/or high density difference between the fluids, gravity forces may still overcome capillary forces and water will cross-flow to the low permeable zone, resulting in reasonable sweep of the Lower zone. However, for thin reservoirs or when cycles of high and low permeable layers exist, small negative capillary forces will be sufficient to hold water in the high permeable layers, see section 5.3.

In summary, to explain the water hold-up phenomenon in this heterogeneous carbonate reservoir, three factors play important roles:

1- The reservoir is non-water-wet, as will be shown in section 6.1, and low permeable layers have higher negative Pc than high permeable layers.
2- Permeability contrast between the Upper and Lower zones where high permeable layers are on top.
3- Cyclicity of relatively high and low permeable layers, which results in low capillary pressure differential required to counter the effects of gravity.

## 5.2 Impact of Cross Flow on Sweep Efficiency

As discussed above, fluid flow in heterogeneous porous media is influenced by cross flow from one stratum to another in a direction perpendicular to the main flow.
To understand the importance of the different forces that control fluid flow seven water/oil displacement scenarios were examined. To quantify the impact of the different physical forces, the recovery factors from the Upper, Lower and total reservoir are compared. The Upper zone consists of 12 layers where 4 low permeable layers are inter-bedded between 8 high permeable layers. The Lower zone consists of 15 layers of low permeability (see Figure 1). The effect of viscous, gravity and capillary cross-flow on water-flood recovery is investigated for the flowing cases:

1- No cross-flow (kv=0)
2- Viscous cross-flow, no gravity, no capillary forces (g=0, Pc=0).
3- Viscous and gravity cross flow, no capillary forces (Pc=0).
4- Water-wet viscous and capillary cross flow, no gravity (g=0, Pc>0).
5- Water-wet capillary, viscous and gravity cross-flow (Pc>0).
6- Oil-wet viscous and capillary cross flow, no gravity (g=0, Pc<0).
7- Oil-wet viscous gravity and capillary cross flow (Pc<0).

All the other parameters are the same in the seven runs. No viscous cross flow was obtained by setting the vertical permeability to zero. No gravity cross flow was obtained by setting the gravity constant g to zero. No capillary cross flow was obtained by setting imbibition Pc to zero. Water-wet and oil-wet capillary cross-flow were obtained by applying positive and negative capillary pressure models, respectively. Runs 3, 5 and 7 are the same as those presented in Figures 2-3. Figures 4-5 show sweep efficiency and the recovery factor of the Upper zone, Lower zone and total recovery factor of the 7 runs as a function of injected water volume (Figure 5 only shows x-z cross section of runs 1,2,4 and 6 as the other 3 runs are shown in Figure 3).

As a first observation, total recovery is strongly dependent on the different forces. Correct representation of these forces in field simulation studies is crucial, otherwise inappropriate recovery mechanism may be implemented in the model which leads to a poor recovery prediction. It is clear from Figure 4, that the recovery factor increases as follows: case 5> case 3> case 4 > case 2 > case 7 >case 6 > case 1. The no cross-flow case has the lowest recovery and the earliest water breakthrough. Case 6 shows that if gravity is ignored and the negative imbibition capillary pressure is high, then recovery and sweep efficiency will approach the no cross-flow case (case 1). In an oil-wet system, capillary pressure prevents (or reduces) cross flow at the leading edge of the water front and results in oil imbibition behind the front from low permeable layers to the swept high permeable layers. However, the former effect dominates and the recovery is reduced.

When total recovery is considered, there is no cross over in recovery between any of the cases. However, cross over of the recovery from the Upper or Lower zone takes place. For example, the positive capillary pressure cases (cases 4 and 5) result in lower recovery of the Upper zone at early time compared to almost all other case, but later in the field life the recovery increases and crosses over that from cases 1, 2, 6 and 7. The possibility of cross over in recovery between the different cases is found to be dependent on geology and injection pressure as the balance of forces will be different depending on those two factors. Therefore, the results reported here maybe different than those reported elsewhere [5] due to differences in geology.

### 5.3 Impact of Geology

In this section we study the impact of permeability contrast on sweep efficiency and oil recovery. The same model was used (3D, 27 layers) but the permeability contrast is changed. Several runs were performed:

1- Permeability of layers 2, 5, 8 and 12 is multiplied by 2.
2- Permeability of layers 2, 5, 8 and 12 is multiplied by 4.
3- Permeability of layers 2, 5, 8 and 12 is multiplied by 2 and permeability of the Lower zone layers is multiplied by 2.
4- Permeability of Lower zone is multiplied by 2 and no change is made to the permeability of the Upper zone.

In the all the runs the kv/kh ratio was kept constant and the same oil-wet capillary pressure model is used (it is the same capillary pressure model used in runs 6 and 7 discussed in section 4.2). The capillary pressure of each layer is scaled to its petrophysical properties, see section 6. Therefore, increasing the permeability of a layer will decrease its capillary pressure, i.e., it becomes less negative. The results of the above four runs are shown in Figures 6-7. Also shown in the figures are the results of the base case run where the permeability is not changed (run 7 discussed in previous section). The results show that increasing the permeability of the low permeable layers in the Upper zone by a factor 4 increases the sweep efficiency of the Lower zone significantly. In this case the Upper zone will act as a one thick gravity head and the negative capillary pressure cannot prevent water cross-flow, i.e., gravity forces dominate. Multiplying the permeability of the Lower zone by a factor 2 has hardly any effect on sweep efficiency or recovery. It is important to note that multiplying the low permeable layers in the Upper zone by a factor 2 improves the recovery of the Lower zone more than multiplying the low permeable zone itself by a factor 2 (compare results of runs 1 and 4).

The results of the runs discussed in this section demonstrate that geological modelling, sequence of layers and preserving low permeability layers in the Upper high permeable zone, has a significant impact on sweep efficiency. The low permeable layers in the Upper high permeable zone act as local barriers and reduce the gravity head.

### 5.4 Impact of Different Capillary Pressure Models

As shown in section 5.1, the sweep efficiency and oil recovery are strongly dependent on whether the capillary pressure is positive, zero or negative. Here we study the impact of different capillary pressure models for the oil-wet case. The base case permeability profile is used and the impact of different oil-wet capillary pressure models is investigated.

To compare the different capillary pressure models, the Pc curves of layers 6 and 14 (Kw of 240 and 5 md, respectively) in the five different models are shown in Figure 8. In the first four cases a different Pc is assigned to each grid cell based on its permeability and porosity. However, in the fifth case the permeability range was divided into seven permeability classes and each permeability class is assigned one Pc curve, i.e., in this last case only seven Pc curves are used. The figure shows very small difference in the capillary pressure curves, which are mainly in either the entry pressure or in the shape of the curves. The results of the runs are shown in Figure 9. The results demonstrate that the shape and magnitude of capillary pressure curves have a significant impact on sweep efficiency. Therefore, proper representation and accurate measurement of capillary pressures is of vital importance. The results clearly emphasize the delicate balance between geological representation and capillary forces, and the resulting impact on predicted performance. It also demonstrates the importance of having an accurate, fine scaled, reservoir description.

## 6. FIELD APPLICATION

As discussed in section 2, water flooding of the reservoir understudy results in water hold-up in the Upper zone. The traditional explanation of a reduced vertical permeability barrier is not supported by core or field data. Core data shows that kv/kh ratios are close to unity even for the low permeability zones. Vertical pressures in infill wells, confirm almost perfect vertical pressure continuity throughout the Upper and Lower zones. This would not be possible with large reduction of vertical permeability. Therefore, a mechanism other than a permeability barrier is impeding injection water from reaching the Lower zone of the reservoir.

The discussion so far has focused on understanding the different factors/forces affecting the water flood performance in a layered reservoir. The discussion demonstrates that capillary forces can explain the water flood performance and impedes injection water from flowing downwards under gravity. However, to confirm that such water flood performance is due to the capillary forces, both laboratory and field data are required. Ideally the concept of negative capillary pressures should be demonstrated by experiments on core material at representative conditions. A laboratory SCAL program was initiated to measure both drainage and imbibition capillary pressure curves. Field data is obtained from observation wells near the injectors to monitor the development of water saturation using time lapse logging. History matching of the saturation logs using measured laboratory data provides confidence in the proposed concept. Moreover, understanding and history matching of the current reservoir performance is essential prior to investigating any alternative recovery process.

## 6.1 SCAL Measurements

A SCAL study was performed to measure capillary pressure curves using core materials from the reservoir understudy. Porosity and permeability of the reservoir rock, as a function of depth, are shown in Figure 1. The SCAL study was performed on 20 selected samples. The core plugs were selected from different rock classes to cover a range of permeability from 0.01 to 1000 mD. Capillary pressure data were obtained in primary drainage (20 samples) and imbibition after ageing the plugs at connate water saturation to restore wettability (10 samples). Figure 10 shows primary drainage and imbibition Pc curves of few samples. The figure shows that as the permeability decreases the drainage capillary entry pressure increases. The imbibition data shows that there is hardly any spontaneous water imbibition, only forced imbibition Pc is measured. This was confirmed by dedicated spontaneous imbibition experiments where water was not imbibed at all in more than a week. The imbibition Pc curves have a weak dependence on permeability where the low permeable plugs show higher negative Pc curves. The negative entry pressure is only 3-5 psi for the plugs of 2-5 md. The data also shows:

1- Distinct differences in the shape of the measured capillary pressure curves for the different permeability classes.
2- The difference in the capillary pressure between high and low permeability plugs (100 md compared to 2-5 md plugs) decreases as the water saturation increases. However, the capillary pressure of plugs of 0.5 md or lower shows a steep increase (becomes more negative) as the water saturation increases.
3- There is very little variation in connate water and residual oil saturation between the different permeability classes especially for permeability higher than 1 md. Both Swc and Sor were measured to be between 5-10%.

## 6.2 History Matching of Field Data

Simulation results discussed in previous sections clearly emphasize the need for incorporating capillary pressure into highly refined models and properly modeling the dependency of the capillary pressure on appropriate variables and rock properties. Dividing the reservoir into upper and lower units or into rock types and representing each unit or rock type by one capillary pressure may lead to erroneous conclusions. Therefore, a capillary pressure model is developed based on the measured data to assign capillary pressure curve to each cell based on its permeability and porosity. The imbibition relative permeability curves were generated using Corey presentations. Note that for the problem at hand, the relative permeability has only a second order impact as compared to the Pc. Therefore, the same relative permeability curves are used in the whole study.

A detailed radial dynamic element model was constructed that includes a production/ injection well pair and a water flood observation well. The vertical resolution in the dynamic model is one foot. The distance between the injector and observer is 500 ft. The porosity and permeability profiles are shown in Figure 1. Figure 11 shows the history match obtained with saturation logs of the observed well. A close match between the observed and calculated saturation profile is achieved. The representation of the water saturation development in the Lower zone, which is the main goal of the exercise, is very good. This history match with the measured SCAL data shows that capillary forces alone can explain field performance with no need for any permeability barriers Setting kv/kh to 0.1 and the Pc to zero slows down the water invasion into the Lower zone. However, the saturation profile that then emerges is very different from the observations.

## 7. CONCLUSIONS

In this paper the effects of capillary forces on sweep efficiency were investigated. SCAL, field and simulation data showed that:

1- Capillary pressure can have significant effects on sweep efficiency and oil production. Capillary forces may act as barriers and results in water hold-up in cases where permeability varies between layers and negative imbibition capillary pressure is present.
2- Detailed static and dynamic modeling in combination with robust design, execution and analysis of a SCAL program, have led to a better understanding of the current reservoir performance under water flooding.
3- A subtle balance of viscous, gravity and capillary forces is found to control fluid flow in this reservoir. Different combinations of these forces can be used to history match the total oil recovery, but they have different production forecasts after water breakthrough.
4- Recovery is strongly dependent on the shape of the Pc curves and the variation in permeability. Preserving low permeability layers in the Upper zone of the reservoir model has significant impact on the reservoir performance predictions as it reduces gravity cross-flow. Production performance (and forecasted profile) and economic Ultimate Recovery will differ under various conditions of wettability, shapes of saturation functions and vertical permeability profiles.

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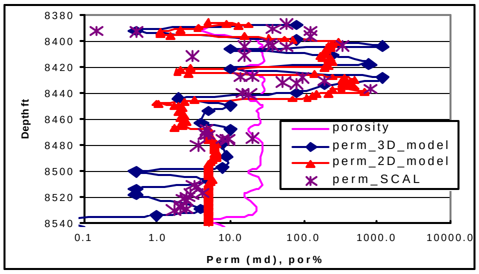


Figure 1: Porosity and permeability of the two models used in the study together with the plugs permeability used in the SCAL measurements.

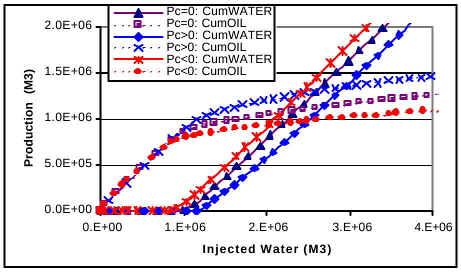
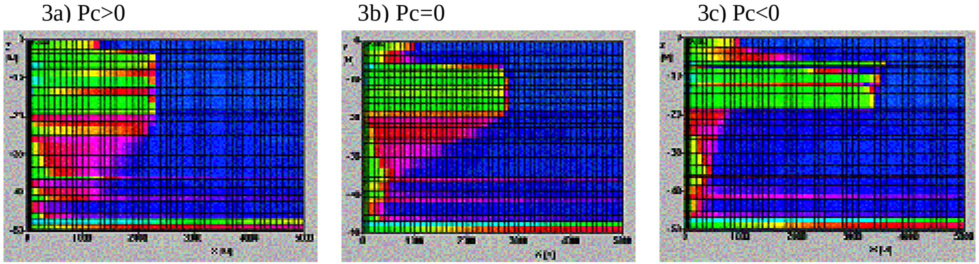


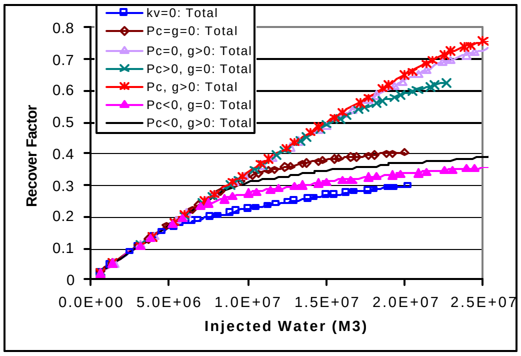
Figure 2: Oil and water production for three different runs with positive, zero and negative imbibition Pc models.


3a) Pc>0

3b) Pc=0

3c) Pc<0

Figure 3: Sweep efficiency of water-wet, neutral-wet and oil-wet cases shown in figure 2



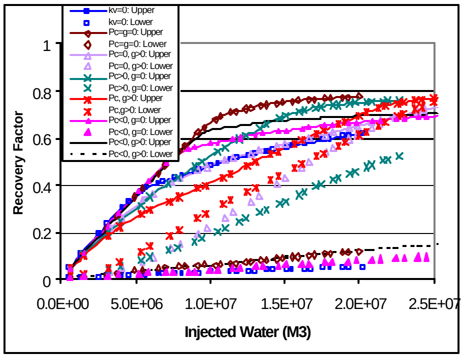
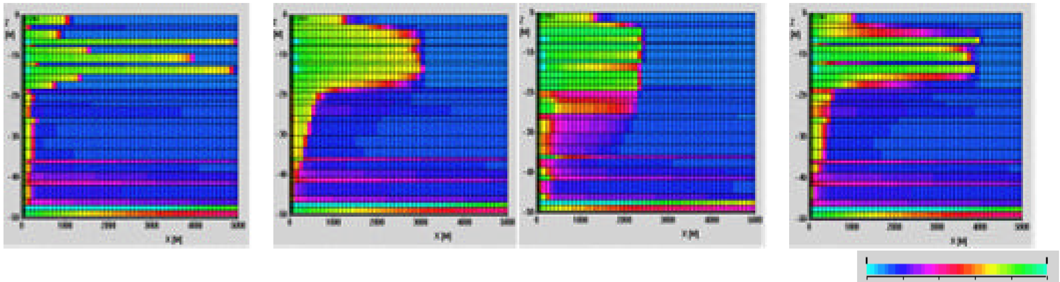


Figure 4: Recover factor from a) whole reservoir and, b) Upper and Lower zones as a function of injected water volume for seven different runs, see text.


5a) Kv=0

5b) Pc=0, g=0

5c) Pc>0, g=0

5d) Pc<0, g=0

Figure 5: Sweep efficiency a) No cross-flow, b) Viscous cross-flow, c) Water-wet capillary and viscous cross-flow, d) Oil-wet capillary and viscous cross-flow. The sweep efficiency of the other three runs discussed in section 5.2 is shown in figure 3.

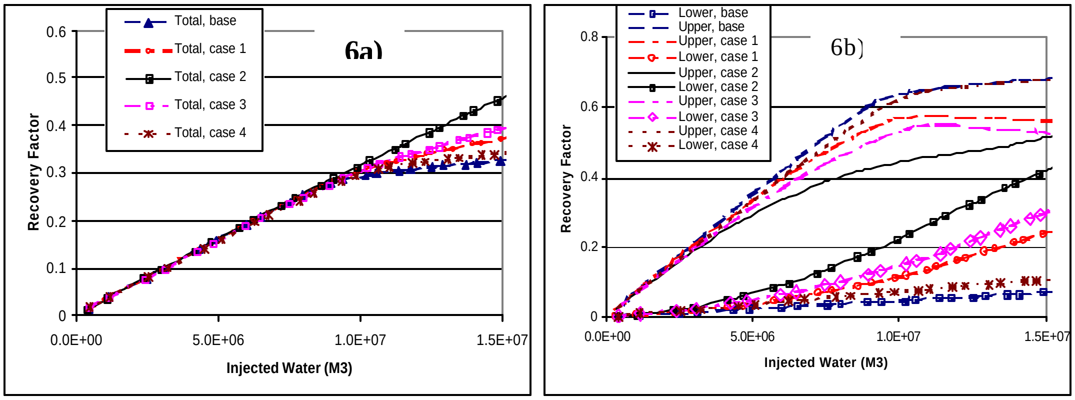
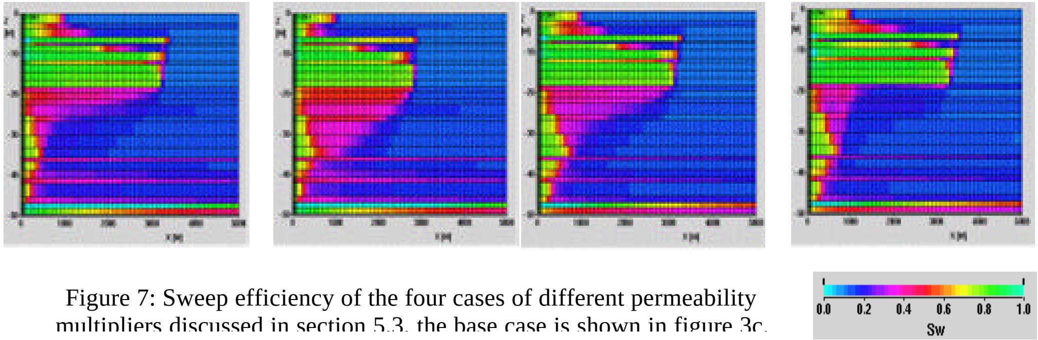


Figure 6: Recovery factor of five different runs using different permeability multipliers in the Upper and Lower zones, see section 5.3. The base case is oil –wet case shown in figure 2 and 3.

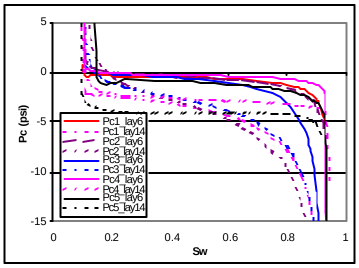

a) case 1

b) case 2

c) case 3

d) case 4

Figure 7: Sweep efficiency of the four cases of different permeability multipliers discussed in section 5.3, the base case is shown in figure 3c.



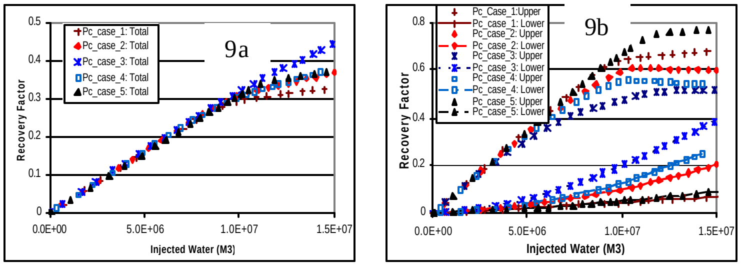


Figure 8: five different Pc models.

Figure 9: Recovery factors of five runs using five different negative imbibition Pc models a) whole reservoir and b) Upper and Lower zones.

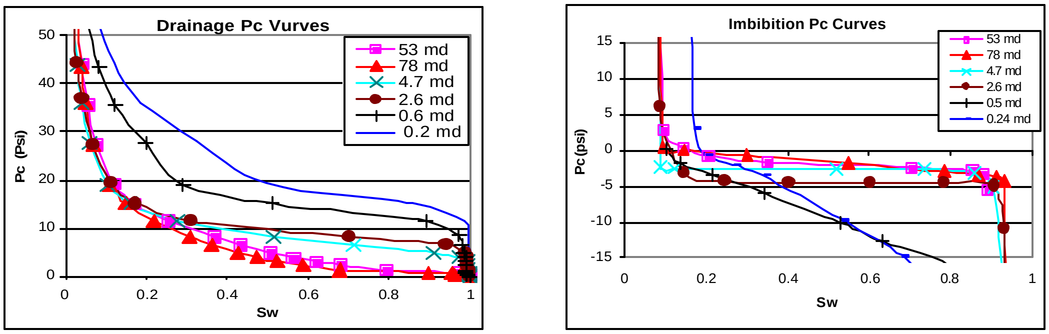


Figure 10: Measured primary drainage and imbibition Pc curves.

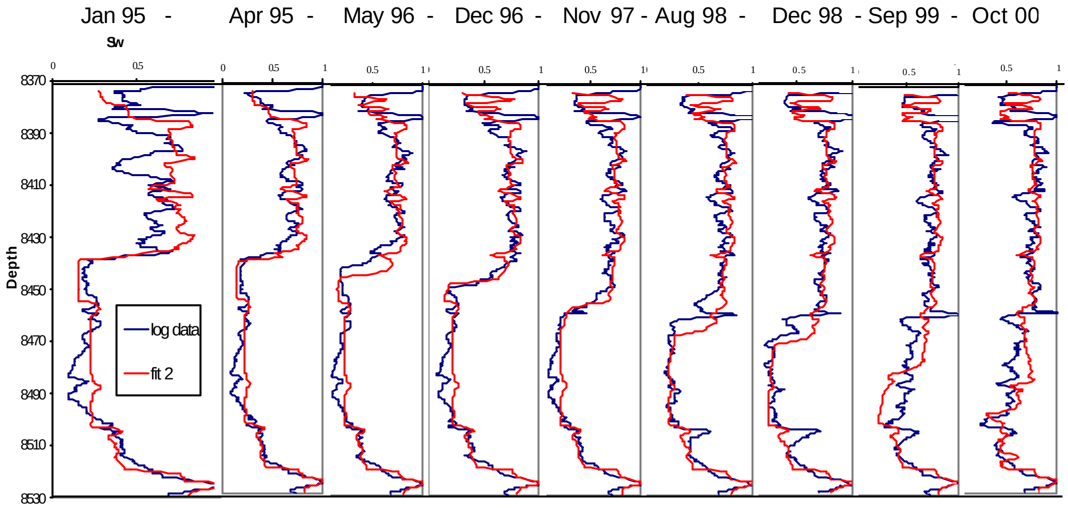


Figure 11: History match of saturation logs using detailed static and dynamic models incorporating the measured imbibition Pc curves.