A NEW METHODOLOGY TO DERIVE BOTH RELATIVE PERMEABILITY AND EFFECTIVE PERMEABILITY REDUCTION PROFILE FROM NUMERICAL SIMULATIONS OF FORMATION DAMAGE EXPERIMENTS

P. Egermann, D. Longeron, F. Lamy
IFP (Institut Français du Pétrole)

ABSTRACT

Near wellbore flow properties are affected by mud and mud filtrate invasion during overbalanced drilling operations. The degree of alteration depends on a large number of parameters such as nature and characteristics of the drill-in fluid, formation properties and operating conditions. Laboratory mud filtration experiments have been conducted for many years to determine the extent and the degree of formation damage due to drill-in fluid invasion.

This paper proposes a new methodology to interpret formation damage tests performed with water-based muds. Numerical simulations are performed to quantify independently, on the one hand the impact of mud solids invasion and on the other hand the effect of multiphase flow process on the global permeability damage. Effective oil return permeability profiles are first determined through local pressure measurements along the core at different backflow rates. Then, corresponding relative permeabilities are determined from matching of the pressure differences and cumulative production evolution as a function of time.

Results show that a good fit between experiment and simulation is obtained with a unique set of relative permeability curves for a given formation permeability. Their shapes are very similar to what is obtained using standard water/oil displacement experiments. The efficiency of the restoration of effective permeability is highly dependent on the oil backflow rate. The higher the imposed oil flow rate, the better the restoration of initial permeability. The main advantage of the proposed procedure is to provide, from a single laboratory test, a consistent interpretation of both permeability damage mechanisms (mud solids deposits and filtrate invasion). This leads to a better diagnosis of the origin of the damage. Finally some recommendations are given to improve the design of laboratory formation damage experiments and to interpret natural cleanup of open hole completed wells. Guidelines are also provided to select the least damaging drill-in fluid formulation for a given permeability formation.

INTRODUCTION

The economic impact of near wellbore formation damage, especially in the case of horizontal wells, often open hole completed, has pushed forward the development of a number of theoretical and experimental studies [1,2,3,4] to assess drilling-induced formation damage and to evaluate the performance of various drill-in fluids proposed by Service companies.

It is well established that the two main damaging processes during overbalanced drilling operations are i) particulate invasion during the initial spurt loss period, in which mud solids are forced into the formation, building an internal filtercake, which can partially plug pore throats, and ii) mud filtrate invasion through the external filtercake, leading sometimes to complex rock/fluid interactions in the invaded zone and creating strong

back to contents

damaging effects. However, mechanisms of formation damage are not always understood and, as reported by Marshall et al[5], laboratory methods are not standardized. Generally oil return permeabilities and cake lift off pressures are directly used to compare the performance of specific drill-in fluid formulations[6,7,8]. These experimental works clearly showed that the Flow Initiation Pressure (FIP) is affected by rock permeability, filtration pressure, flow-back rate and mud type. More recently Sharma and Zain[9] presented a simple model for estimating filter cake lift off pressure during flow back of core samples damaged with sized-$CaCO_3$ and sized-salt muds. They demonstrated that the Flow Initiation Pressure was directly correlated with the extent of solids invasion and it represents mostly internal core cleanup rather than actual filter-cake removal. In addition, Ladva et al[10] showed, from laboratory tests and numerical simulations, that the pressure drop response during backflow is affected by multiphase flow effects. Therefore, FIP values must be assessed with caution when comparing oil-based and water-based muds performance.

Even in the absence of physico-chemical reactions between filtrate and formation fluids (compatible rock/fluid systems), there is a fundamental difference between water-based and oil-based mud invasion of the near wellbore. In a water-wet oil bearing formation, the displacement of the oil in place with a filtrate generated from an oil-based mud is a miscible displacement process while the oil displacement with a filtrate generated from a water-based mud is an imbibition process leading to high wetting phase saturations in the invaded zone. In this case, when the well is put in production during the oil backflow, a portion of the wetting phase is trapped (secondary drainage process), leading to residual wetting phase saturations higher than the initial (connate) ones. This induces an adverse water/oil relative permeability effect, which is an additional permeability impairment[11].

This paper is a contribution to the understanding of damaging mechanisms induced by water-based muds. A methodology is proposed to interpret the oil return permeability measurements conducted at different flow rates on core samples damaged with typical polymeric water-based muds. Laboratory tests are interpreted with a 1-D numerical model in order to quantify separately the effect of mud solids invasion and the impact of filtrate trapping on the permeability impairment as a function of the distance to the wellbore.

EXPERIMENTAL PROCEDURES

Laboratory Equipment for Dynamic Mud Leak off Tests on Long Core Samples

A full description of the equipment developed at IFP can be found in a previous SCA paper[12]. Let us recall that it mainly includes (Figure 1):

- a dynamic filtration core-holder cell which can accommodate samples of 5 cm in diameter and up to 40 cm long. The cell is equipped with five pressure taps located at 5, 10, 15, 20 and 25 cm from the inlet face of the core. Special care was taken to design the end-piece of cell. A rectangular channel through which the mud flows parallel to the inlet face ensures steady shear rate on the deposited mud cake. Pressure taps allow monitoring of the pressure drops across six sections of the core while circulating the mud and while backflushing the oil to simulate the well production. This allows us to calculate permeability impairment as a function of the distance from the damaged face of the core.

- a mud circulating system including a rotary diaphragm pump to generate laboratory mud flow rates (up to 11 L/min) which represent typical mud velocities occurring in the well
- a back pressure regulator valve and various dampeners and mud containers.
- an oil and brine injection device including a positive displacement pump and cells which contain oil and brine to saturate the core and measure oil return permeabilities.
- various measurement systems including temperature and pressure transducers and an automatic weighting device for measuring the oil and filtrate production as a function of time.
- an automatic computer controlled data acquisition system.

Rock and Fluids Used

Two experiments, performed on Berea sandstones during an extensive laboratory study, are presented to demonstrate the methodology for interpreting the oil back flow process on samples damaged with two typical water-based muds.

The first experiment was made on a high permeability sample (kg = 2100 md) of 33 cm length, damaged with the mud formulation F1 (standard salted polymeric mud), weighted with 360 g/L of calcium carbonate particles to reach a specific gravity of 1.30 kg/m^3. The second experiment was made on a medium permeability sample (kg = 641 md) of 10.4 cm length, damaged with the mud formulation F2, weighted with 150 g/L of calcium carbonate particles to reach a specific gravity of 1.10 kg/m^3. Both weighting particles have the same average size, D 50 = 5.2 µm. The compositions of the mud formulations are given in Table 1.

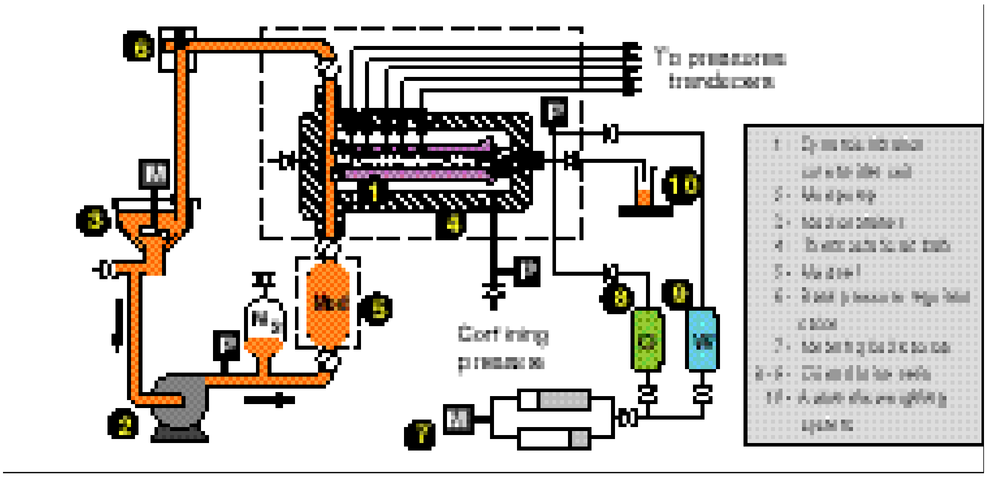


Figure 1: experimental apparatus

Core preparation

After selection based on CT scanning examinations, the cores were cleaned, dried and their gas permeability was measured. The core samples were saturated with a 30 g/L NH_4Cl brine and pore volume and brine permeability were measured. Then, irreducible water saturation, S_{wi}, was established by flooding with a high viscous mineral oil (µo = 110 cP). Finally the viscous oil was miscibly displaced at low flow rate with Soltrol 130

(μo= 1.6 cP) until stabilization. Then oil permeability in the presence of S_{wi} was measured at 3 flow rates and taken as the reference ”undamaged initial permeability”. The dimensions and main petrophysical characteristics of the core samples are given in Table 2.

Mud Leak off Tests and Return Permeability Measurements

The mud leak off tests were performed at 60°C and under 20 bars of overbalance pressure. For the Test 1, the duration of the dynamic mud exposure was about 12 hr under a shear rate of 180 s^{-1}. The total fluid loss was 48.3 cc, corresponding to about 31.8 % PV. Then, successive oil back flow rates of 30, 60, 120 and 500 cc/hr were applied to measure oil return permeabilities.

For the Test 2, a dynamic mud exposure of 1hr at a shear rate of 180 s^{-1} was followed by a static mud exposure of 22 hours. The filtrate BT was observed before the end of the mud exposure when the total fluid loss was 26 cc. This volume corresponds to about 57% PV. Then, oil back flow rates as those used in Test1 were applied to determine oil return permeability values.

The cumulative fluid losses as a function of the mud exposure time are presented in Figure 2 for both tests. One can see that spurt losses and filtration rates vary greatly from Test 1 to Test 2. This is due to the combined effect of the permeability and the mud solids concentration.

Formulation 1		Formulation 2	
Component	Composition g/L	Component	Composition g/L
Xanthan	4	Viscosifier	11
Starch	11.4	Filtrate reducer	14
Drill solids	28.5	KCl	55
NaCl	20	PH buffer	1
KCl	20	CaCO3 5 µm (weighting agent)	150
CaCO3 5 µm (weighting agent)	360		

Table 1:composition of water-based muds

Test n°	Length (cm)	Diameter (cm)	kg (md)	ϕ (%)	Swi (%PV)	ko (md)
1	33	4.9	2100	24.4	25.6	1982
2	10.4	4.95	641	22.5	22.9	564

Table 2: core samples characteristics

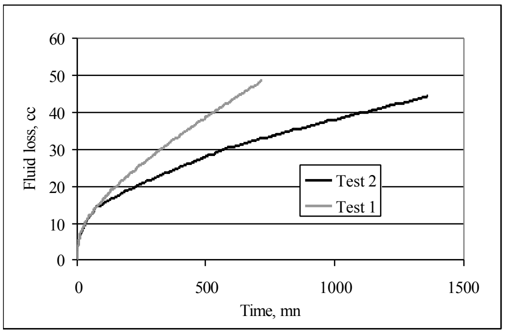


Figure 2: filtration curves during the damaging period

INTERPRETATION OF THE EXPERIMENTAL DATA

The global permeability damage, deduced from the backflow measurements is the result of i) a reduction of the intrinsic permeability due to the solid particles invasion and ii) an unfavorable water/oil relative permeability effect linked to the trapping of wetting phase during secondary drainage processes. This global damage is commonly represented as a function of the distance from the damaged face of the core without any attempt to separate the origin of the damage. We propose hereafter a methodology to decouple these effects in order to distinguish the real contribution of each on the global permeability impairment.

Determination of the intrinsic permeability reduction

When mud just starts infiltrating at the face of the core, there is no external filter cake to prevent mud solids particles to enter the porous medium. During this period (spurt) there is a progressive deposition of these particles in the vicinity of the damaged face (internal filter cake). When the internal filter cake is well established, most of the solid particles are retained outside of the core, creating an external filter cake, which controls the rate of filtrate invasion. Hence, two regions in the core sample can be distinguished, regarding the solid particles deposition that reduces the intrinsic permeability:

- deposition near the damaged face. During the backflow process, this region is subjected to the combined effect of the intrinsic permability variation and the relative permeability effect.
- insignificant deposition far from the damaged face. Only the relative permeability effect has to be considered.

In our methodology two main assumptions are made. The core is supposed to be long enough to obtain the two regions described above. According to our experience, this condition is fulfilled with a core length above 10 cm. The second assumption considers that the average wetting phase saturation (water and filtrate), derived from the volumetric balance between injected and produced fluids during the back flow, is uniform along the core.

The calculations follow several steps:

- Determination of k_{ro} at S_{wr} from the region least exposed to the solid particles deposition (last pressure tap and the outlet pressure).
- Determination of expected k_o profile with the k_{ro}@S_{wr} value and the initial permeability profile.
- Determination of the effective value of k_o measured from the lateral pressure taps.
- Evaluation of the permeability reduction profile.

Table 3 gathers the results obtained for Test 1 at the end of the different steps of the backflow period. All the profiles end at 1 as the outlet of the core is the normalization area. Figure 3 shows that the corresponding profiles do not change so much at low rate (from 30 cc/hr to 120 cc/hr). Only the profile obtained after the highest rate (500 cc/hr) brings significant improvement of the permeability profile. This suggests that the higher the backflow rate, the lower the permeability reduction.

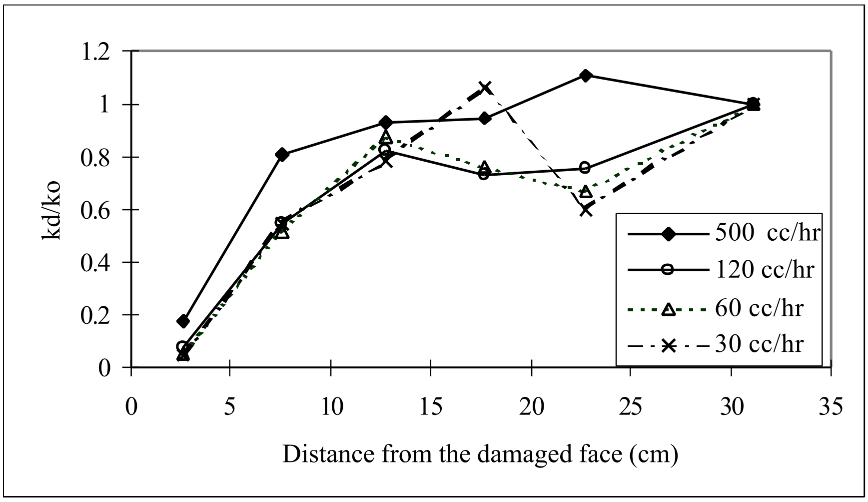


Figure 3: Evolution of the permeability reduction along backflow rate

Core section	0-5 cm	5-10 cm	10-15 cm	15-20 cm	20-25 cm	25-33 cm	kro @ Swr	Swr
ko at Swi md	1867	1982	1960	2138	1847	1970		
Return pereability (kd/ko, fraction) at the end of each of the backflow rate period								
30 cc/hr	0.04	0.54	0.78	1.05	0.60	1	0.36	0.45
60 cc/hr	0.05	0.51	0.87	0.76	0.67	1	0.46	0.41
120 cc/hr	0.07	0.54	0.82	0.72	0.75	1	0.60	0.37
500 cc/hr	0.17	0.80	0.93	0.94	1.11	1	0.64	0.32

Table 3: permeability reduction factor profiles for Test 1

Table 3 also shows that 4 points of the corresponding oil relative permeability curve can be deduced (S_{wr} is derived from the filtrate recovery curve).

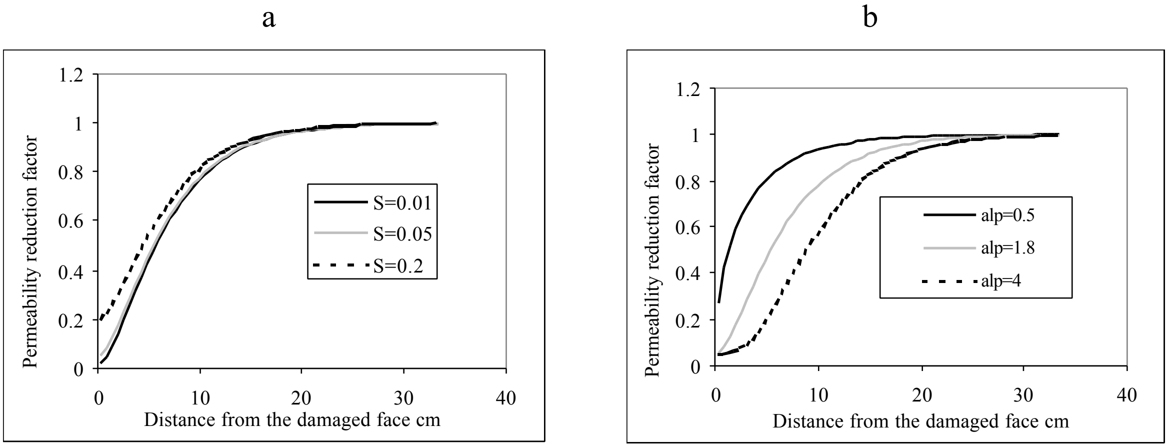
Parameterization of the permeability profile

The previous section has revealed the typical shape of the effective permeability profile. The reduction is severe near the damaged face whereas it tends asymptotically to zero when the distance from the face increases. The main advantage of the proposed model is to use 3 parameters that can be related to a physical aspect of the core damage:

$$k(x) = kini \times (1 - S) \times (1 - \exp(-\frac{x}{Xe}))^{a} + S$$

- S (without dimension): represents the permeability reduction factor at the damaged face. It gives the amplitude of the damage in the neighborhood of the external filter cake.
- Xe (length dimension): is directly related to the damage depth into the core from the filtrating face.
- α (without dimension): enables to describe the shape of the permeability reduction along the core. This parameter should depend on the way the core has been damaged: duration, mud type, porous medium, ...).

The influence of each of the parameters on the permeability reduction profile is explored on Figure 4 a, b and c.



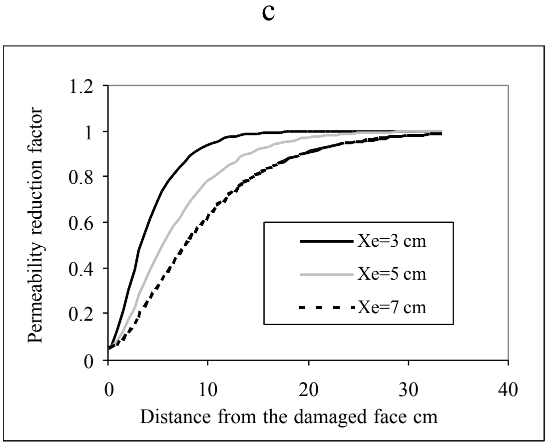
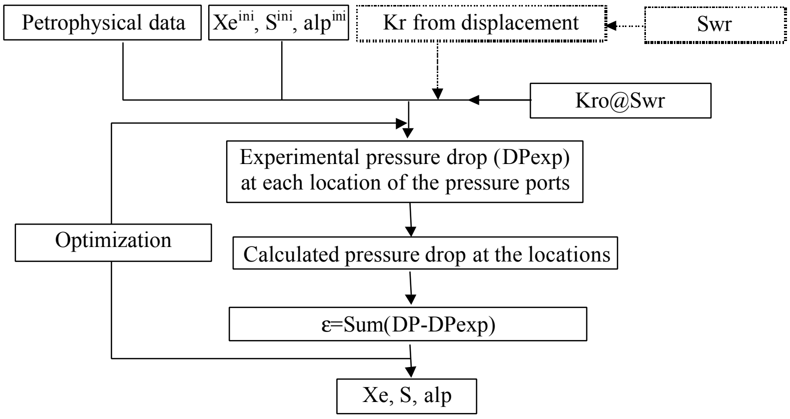


Figure 4: Influence of the parameters values on the permeability reduction profile

Inversion procedure

The model is now applied to the data calculated in Table 3. The parameters were determined by an optimization procedure using the Newton technique. The inversion loop is described on Sketch 1. The corresponding results are given in Table 4.



Sketch 1: principle of the inversion loop

rate cc/h	S	Xe	Alp
60	0.021	4.93	3
120	0.034	5.42	2.82
500	0.044	2.67	2.29

Table 4: parameters values at different step of the backflow

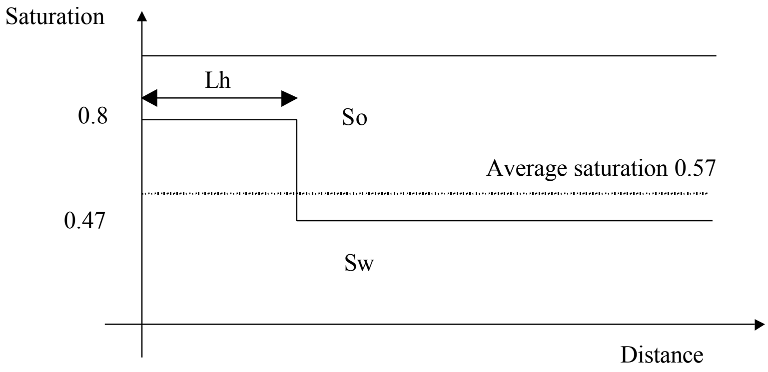
The results given in Table 4 are consistent for Xe and Alp whatever the initial values introduced before starting the inversion loop. However, S is very sensitive to the initial value that is implemented. This behavior is certainly related to the nature of this parameter, which is very sensitive to the value of the permeability in the vicinity of the damaged face. As the spacing between the lateral pressure taps is constant, the experimental data density is not high enough near the damaged face to enable correct determination of S. A strong reduction of Xe is observed after the maximum clean-up rate (500 cc/hr). This means that the damaging depth is reduced. Alp also decreases, which suggests that the profile shape has changed. In spite of the lack of accuracy, it seems that S tends to increase with the value of backflow rate. This parameterization was implemented in a 1D, two-phase, incompressible simulator in order to perform the history match more easily.

HISTORY MATCH OF THE LONG CORE EXPERIMENT

Simulation data set

The principle of the history matching is similar to the one used to interpret a standard immiscible oil/water displacement experiment. The only difference is that the work is conducted stepwise because the permeability profile changes during the back flow. As a first approach, we have considered that the permeability profile is stable for a given backflow step (ie a constant backflow rate). The profile is modified at the beginning of the next step.

In terms of saturation after damage, only the average value of the filtrate saturation is known from the volume of oil produced during the damaging period. The shape of the profile can only be inferred, as local saturation measurements are difficult to conduct due to the nature of the mud. Nevertheless, it is recognized that the filtrate saturation is higher in the vicinity of the damaged face. Figure 4 presents a typical step-invasion profile (Sketch 2).



Sketch 2: filtrate saturation profile after invasion

The extension of the high saturation region (Lh) roughly corresponds to the infiltrated volume during the “spurt” period (around 20 cc). Assuming that S_{or} is equal to 0.2, it gives a length Lh equal to about 8 cm. The rest of the filtrated volume, which corresponds to the filtrate invasion period, is then distributed homogeneously in the remaining part of the core.

$$\text{Lh} = \frac{\text{Filtrate volume}}{A \times f \times (1 - S_{wi} - S_{orw})}$$

It has to be noted that the estimation of Lh (8 cm) is higher than 5 cm, the value of Xe found at the end of the low backflow rate period. This result is logical since Lh corresponds somehow to the initial value of Xe.

RESULTS

Pre-analysis of the Pressure Difference during back flow

The pressure drop (DP) evolution is characterized by a rapid increase during the first minutes of the injection up to a maximum, which is called FIP (Flow Initiation Pressure). Then, DP decreases and stabilizes to a constant value. The production curve clearly shows that the oil breakthrough occurs only one hour after the beginning of the backflow. Hence, the pressure peak does not result from a multiphase flow phenomenon. Two main periods are observed in a long core experiment:

- The first one corresponds to the sharp increase of DP and is related to the presence of the external filter cake. DP reaches the FIP value when the filter cake starts breaking (pinholes or complete/partial removal).
- When the external filter cake stops participating in the flow resistance, DP drops significantly and its evolution is only controlled by the oil injection. Besides, a variation of the DP evolution is observed at a time which corresponds exactly to the oil breakthrough (decrease of DP becomes more pronounced).

Simulations

A very good history match is obtained for each step of the backflow period as shown on Figure 5 and Figure 6. The corresponding water/oil relative permeabilities are given in Figure 7. The curves are close to those obtained from a standard immiscible displacement conducted on a water-wet Berea core sample of the same permeability.

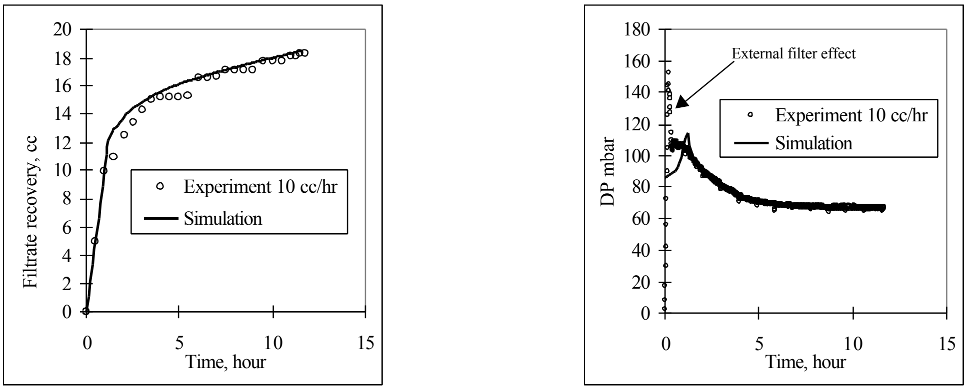


Figure 5: History matching of the LOP period (10 cc/h)

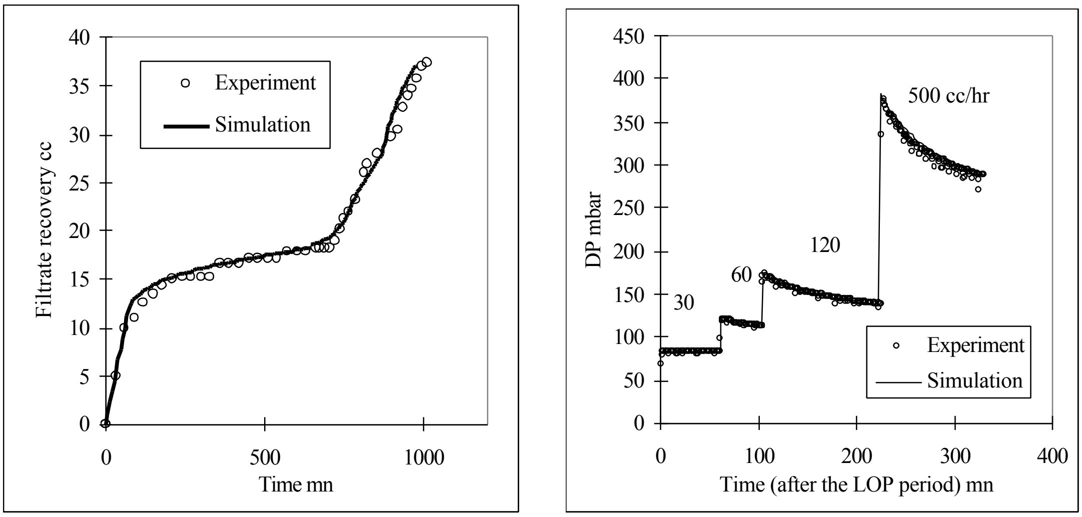


Figure 6 : history matching for higher rate (above 30 cc/h)

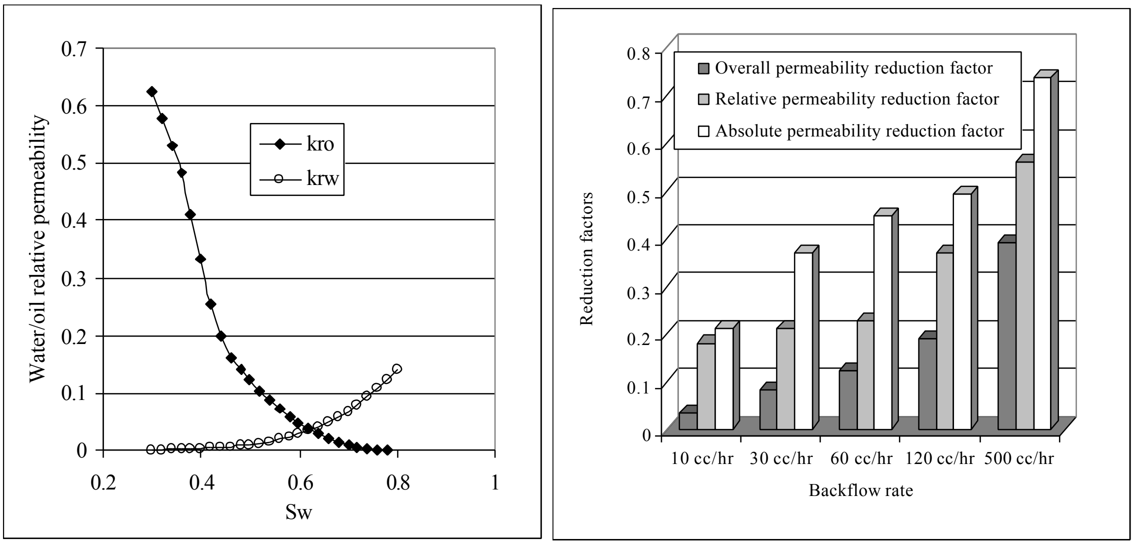


Figure 7 : result of the history matching of the long core experiment

As $k_o = k \times k_{ro}$, the overall permeability reduction (OPR) can be written as the combined effect of the two contributions that have been decorrelated through our approach:

$$\mathrm{OPR} = \frac{k_o @ S_{wr}}{k_o @ S_{wi}} = \frac{\bar{k}}{k_o @ S_{wi}} \times k_{ro} @ S_{wr} = R_k \times R_{kr}$$

R_k results from the impairment due to the internal filter cake whereas R_{kr} is directly related to the oil relative permeability at the given residual water saturation. $\bar{k}$ is obtained by harmonic averaging of the permeability profile along the core.

The result of the respective contribution is given on Figure 7. It shows that the level of return productivity depends on both effects. Both R_k and R_{kr} increase with the backflow rate but not in the same way. Due to the curvature of the oil relative permeability, the increase of R_{kr} is more pronounced at the high oil flow rates.

HISTORY MATCH OF THE SHORT CORE EXPERIMENT

Approach

The nature of the history match is different, since no intermediate pressure differences were available to apply the above approach. Moreover, filtrate recovery was not recorded except at the end of the back flow, so only the end-point of saturation was determined. Hence, the relative permeability curves were assumed (Figure 8) and the history matching was performed on the pressure differences at the different oil flow rates. The water/filtrate saturation was considered uniform before starting the backflow period due to the short length of the core.

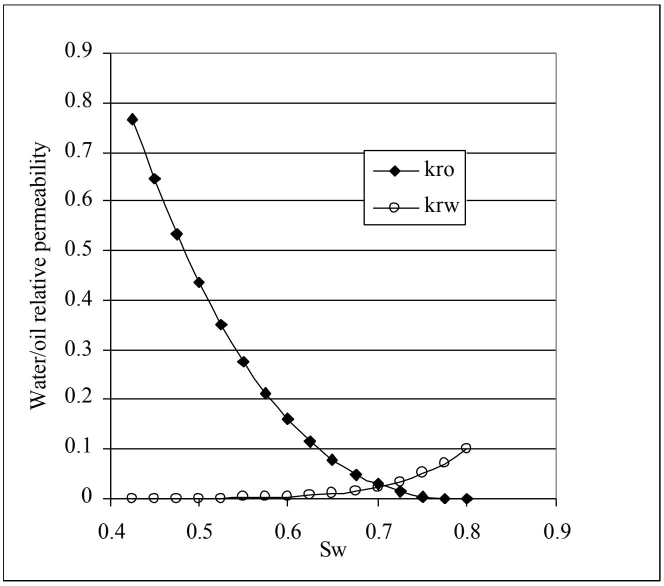


Figure 8 : water/oil relative permeability curve used for the history matching

Figure 9 shows that a satisfactory history matching is obtained. As the external filter cake was removed prior to the backflow period, the pressure drop response is not altered and the peak pressure corresponds to the oil breakthrough time. The corresponding permeability profiles are plotted on Figure 10. The evolution of the permeability profile suggests that the internal filter cake removal is highly dependent on the backflow rate applied, as it was also observed on the long core experiment and in the previous work of Sharma and Zain[9].

CONCLUSIONS

A new methodology is proposed to interpret the backflow process on core samples damaged with water-based muds. The main advantage is to provide, from a single laboratory test, the contribution of both internal filtercake and multiphase flow effects on the global permeability reduction. This leads to a better diagnosis of the origin of the permeability impairment. The results show that the residual permeability damage is strongly related to the oil backflow rate. This means that it is particularly important to evaluate return permeability at relevant flow rates, similar to the ones generated in the well.

Drilling fluids are typically designed to have minimal fluid loss and solids invasion. It is also important, however, to design fluids that clean up easily during backflow. FIP is an important parameter to characterize the effectiveness. The numerical simulations of the backflow process show that the aqueous trapping phase significantly contributes to the damaging mechanism. It is recommended to perform drilling mud invasion tests on long core samples with pressure taps to monitor the pressure differences as a function of the distance from the inlet face of the core. When short cores are used, an interpretation is also possible if water/oil relative permeability curves are used as input data. In all cases, it is recommended to perform oil backflow at different rates to exactly simulate what happens when the well is put under production.

The methodology could be improved by introducing an analytical law for oil return permeability variation as a function of the flow rate to avoid making the history matching by pieces. The goal is to modify the permeability profile dynamically during the backflow experiment depending on the key parameters that affect the internal filter cake. This work is currently in progress and will be introduced into a near wellbore model.

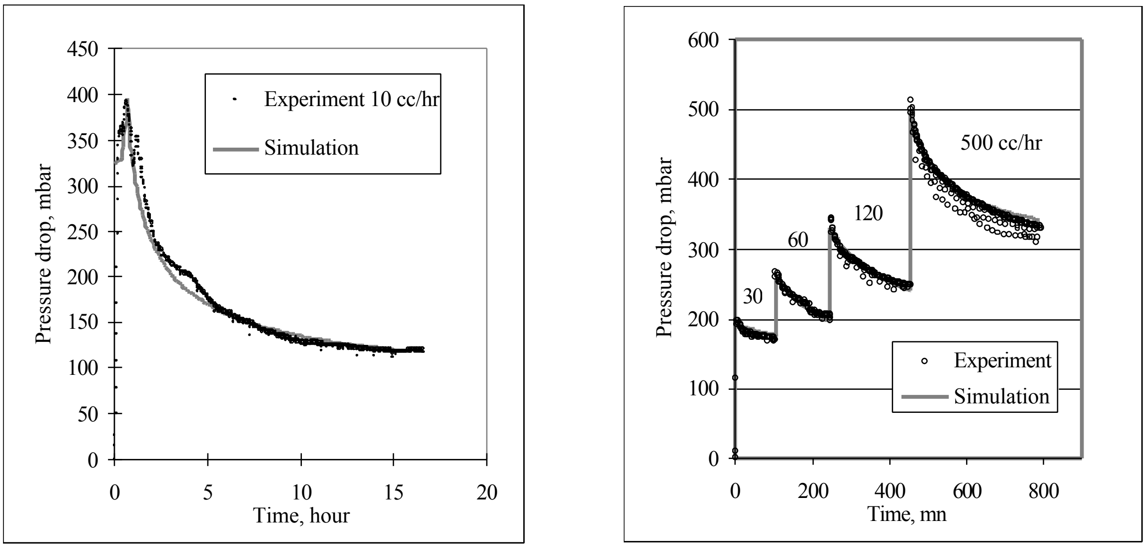


Figure 9 : history matching of the pressure drop on the short core experiment

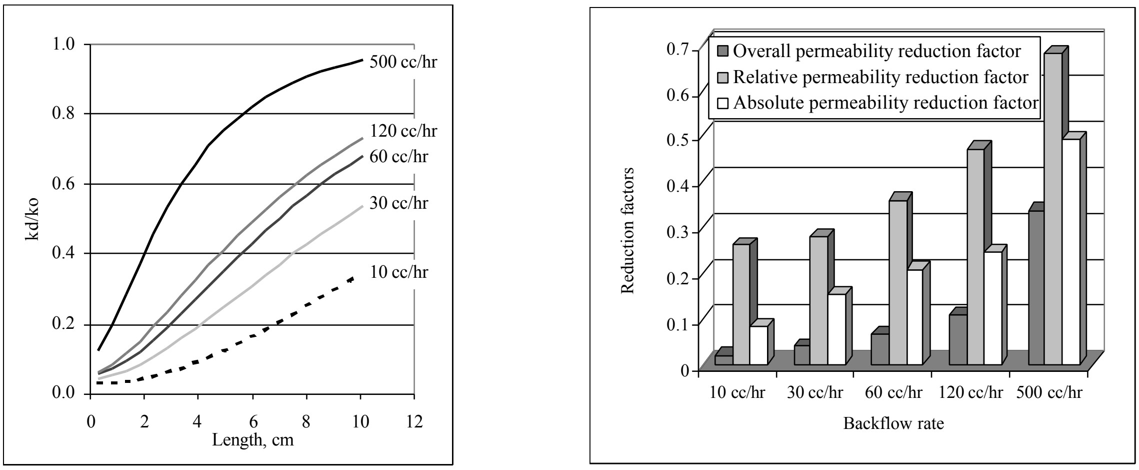


Figure 10 : results of the history matching of the short core experiment

NOMENCLATURE

A:	Area	S_{wi}:	Irreducible water saturation
Alp:	Shape exponent	S_{orw}:	Residual oil saturation
DP:	Pressure drop	ϕ:	Porosity
k:	Permeability	OPR:	Overall permeability reduction factor
ki:	Permeability of phasi i	Rk:	Permeability reduction factor
kri:	Relative permeability of i	Rkr:	Relative k reduction actor
S:	kini/k on the damaged face	Xe:	Internal filter cake depth
Si:	Saturation of phase i	kini	Initial permeability

REFERENCES

1 Shaw J.C., Chee T.: ’’ Laboratory evaluation of drilling mud systems for formation damage prevention in horizontal wells’’, SPE n°37121, Int Conference on Horizontal Well Technology, Calgary, 18-20 November, 1996.

2 Adair K.L., Gruber N.G.: ’’ New laboratory procedures for evaluation of drilling induced formation damage and horizontal well performance: an update’’, SPE 37139, Int Conference on Horizontal Well Technology, Calgary, 18-20 November, 1996.

3 Van der Zwaag C.H., Stallmach F., Basan P.B. et al: ’’ New methodology to investigate formation damage using non-destructive analytical tools’’, SPE 38161, European Formation Damage Conference, The Hague, 2-3 June, 1997.

4 Bailey L., Boek E.S., Jacques S.D.M. et al: ’’ Particulate invasion from drilling fluids’’, SPEJ , Volume 5, n°4, December , 2000.

5 Marshall D.S., Gray R., Byrne M.T. :"Return permeability: a detailed comparative study", SPE 54763, European Formation Damage Conference, The Hague, 31 May-1 June 1999.

6 Ryan D.F., Browne S.V., Burnham M.P.: ’’ Mud clean-up in horizontal wells: a major joint industry study’’, SPE 30528, ATCE, Dallas, 22-25 October, 1995.

7 Browne S.V., Smith P.S.: ’’ Mudcake cleanup to enhance productivity of high-angle wells’’, SPE 27350, Int Symp on Formation Damage Control, Lafayette, 7-10 February, 1994.

8 Longeron D.G., Alfenore J., Salehi N., Saintpère S. :"Experimental approach to characterize drilling mud invasion, formation damage and cleanup efficiency in horizontal wells with openhole completions", SPE 58737, Int. Symp on Formation Damage Control, Lafayette, 23-24 February 2000.

9 Sharma M., Zain Z.: ’’ Model simplifies filter cake lift-off pressure determination’’, Oil and Gas Journal, 1 November, 1999.

10 Ladva H.K.J., Tardy P., Howard P.R.: ’’ Multiphase flow and drilling fluid filtrate effects on the onset of production’’, SPE 58795, Int. Symp on Formation Damage Control, Lafayette, 23-24 February, 2000.

11 Bennion D.B., Cimolai M.P., Bietz R.F., Thomas F.B.: ’’ Reductions in the productivity of oil & gas reservoirs due to aqueous phase trapping’’, CIM n°93-24, Calgary, 9-12 May, 1993.

12 Longeron D.G. :"SCAL: an indispensable step for formation damage evaluation", SCA 2015, Abu Dhabi, 22-24 Oct 2000.

back to contents